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Microwave processing of sewage sludge

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Microwave Processing of Sewage Sludge

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To my mother and father.

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Summary

Traditional disposal methods of sludge, such as ocean disposal, burial in landfills and incineration in some cases, has received much criticism and public disapproval on a world wide scale. With this in mind, the Sydney-Illawarra-Blue Mountains Water Board has been looking at new technologies of sludge disposal or reuse, to establish their viability. This thesis is a detailed investigation of microwave processing of sewage sludge, concentrating on the design and testing of an experimental 40kW continuous microwave pasteurisation and sterilisation plant.

Extensive testing of this plant was carried out at Shellharbour Sewage Treatment Plant. Results indicated, pasteurisation of sludge was achieved at parameters varying from 66°C for at least 10 minutes to 95°C for at least 5 minutes. Sterilisation was achieved at a treatment temperature of 125°C and a residence time of 10 minutes.

Further testing was carried out on a 60kW dedicated microwave pasteurisation plant that evolved from the successful work on the 40kW plant. This plant was also installed at the Shellharbour Sewage Treatment Plant and trials were undertaken to determine parameters for recently adopted United States Environmental Protection Agency (EPA) regulations of "Class A" pathogen reduction.

Tests conducted showed this plant was effective in pasteurising sewage sludge and results indicated Class A pathogen reduction (or pasteurisation) was achieved, for a treatment temperature of 86°C and a residence time of at least 6 minutes. These results were found to be directly comparable with results obtained from the 40kW experimental plant.

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Nomenclature

A	cross-sectional area (m^2)
c	speed of light (cm/s)
Cp	specific heat pressure constant (kJ/kg ^oC)
d	penetration depth (m)
D	diameter (mm)
e	exponential
E	electric field strength (V/m)
f	frequency (Hz)
g	gravity (m/s^2)
h	enthalpy (kJ/kg)
h_f	head loss (m)
I_A	current (A)
k'	relative permittivity, dielectric constant
k"	loss factor
K	loss coefficient
$\dot{m}$	mass flow rate (kg/s)
p_{yp}	yield pressure (kPa)
P	power at penetration depth (W)
P_D	power dissipated (W/m^3)
P_{mic}	microwave power (W)
P_0	incident power (W)
Q	volumetric flow rate (m^3/s)
$\dot{Q}_{cv}$	rate of heat transfer (kW)
Q_T	total volumetric flow (m^3/s)

r_i	inside radius (mm)
r_o	outside radius (mm)
R_e	Reynolds number
U	velocity (m/s)
V_l	voltage (V)
$\dot{W}_{cv}$	rate of work (W)
Z	elevation (m)

Greek symbols

α	attenuation constant
$\tan\delta$	loss tangent, dissipation factor
ΔT	change in temperature (^oC)
ε^*	complex permittivity (F/m)
ε_o	dielectric permittivity (F/m)
η	efficiency (%)
η_s	effectiveness (%)
λ_o	wavelength in free space (cm)
μ	absolute viscosity (Pa s)
ρ	density (kg/m^3)
σ_{yp}	yield strength (MPa)

Subscripts

e	exit state
i	initial state
n	1,2,3,....n
t	total

1. Introduction

1. Introduction

There has been an increasing demand in Sydney and around the world to improve the quality of waste water discharges. This demand has resulted from stricter regulations developed by government in response to professional and public concern. This has led to the quality of effluent improving, which has increased the amount of sludge collected. Forecasts also indicate that the quantity of wastewater sludge will dramatically increase in the near future.

Traditional disposal methods of sludge, such as ocean disposal, burial in landfills and incineration in some cases, have recently received much criticism and public disapproval on a world wide scale. With this in mind, the Water Board has been looking at new technologies of sludge disposal or reuse, to establish their viability.

This thesis is a detailed investigation of microwave processing of sewage sludge, concentrating on the design and testing of an experimental 40kW continuous microwave pasteurisation and sterilisation plant. Immediate potential applications of such a plant would be for the treatment of sludge for use as a soil conditioner. It could also be useful for any other process which may require immediate sludge treatment to levels from pasteurisation to sterilisation.

Design manufacture and initial testing of this plant on water was carried out at the Microwave Applications Research Centre (MARC), Coniston Industrial Laboratory University of Wollongong and extensive testing on sewage sludge was carried out at Shellharbour Sewage Treatment Plant (STP)

Further testing was carried out on a 60kW dedicated microwave pasteurisation plant that evolved from the work on the 40kW plant. This plant was also installed at the Shellharbour STP and trials were undertaken to determine parameters for recently adopted American Environmental Protection Agency (EPA) regulations of "Class A" pathogen reduction.

Chapter 2 discusses areas of applied research and development work undertaken by the MARC, concentrating in particular on background work conducted on the treatment of sewage sludge using microwave energy.

Chapter 3 is a literature review of sewage sludge, microwave technology and related pasteurisation technology. This overview looks at the present and projected sludge quantities handled by the Water Board, current sludge use and disposal options, regulations and guidelines. A summary of microwave technology investigates the history and advantages of microwave energy and includes a world wide summary of industrial microwave installations. A review of related pasteurisation work is also presented.

Chapter 4 presents the theory and analysis required for effective design and evaluation of the process. Microwave theory outlines microwave characteristics, heating mechanisms, energy conversion and penetration depth. Other theories presented are the continuity equation, first law of thermodynamics, efficiency, effectiveness and fluid resistance.

Chapter 5 deals with the design of the 40kW plant. It investigates appropriate microwave applicator technology, pump and pressure treatment processes, heat exchanger use and magnetron cooling water design. Instrumentation for evaluation of the process is also considered.

Experimental results are presented in chapter 6. The heating rate of sludge in comparison to water was investigated using a 1300 watt domestic microwave oven. The 40kW plant was commissioned at MARC's Coniston laboratory and results of preliminary testing utilising water are presented. The plant was relocated to Shellharbour STP where extensive testing on digested sewage sludge was conducted. Results are tabulated. Parameters used for process evaluation were maximum temperature attained by the sludge and residence time of the sludge at this temperature.

Chapter 7 utilises the results presented in chapter 6 to propose appropriate parameters for pasteurisation and sterilisation of sewage sludge. Effectiveness of the process was also investigated.

Chapter 8 outlines the description, design and test results of a dedicated 60kW microwave pasteurisation plant that evolved from the success of the 40kW plant. Testing was carried out to determine if the plant could produce sludge which meets recently adopted American EPA regulations for class A pathogen reduction. Effectiveness and economics of the plant was investigated. Suggestions for improvements and further work are also given.

Chapter 9 concludes this thesis by listing pertinent findings.

2. Background

2. Background

2.1 The Microwave Applications Research Centre

Conventional heating operations may utilize heat transfer by conduction, convection, radiation or a combination of any of these mechanisms. Regardless of the heat transfer mechanism, the heat must flow to the outer surface first and then to the interior. An exception to this is heating with high frequency radiation such as microwaves, which have the ability to penetrate and heat both the surface and the interior of material. In recognition of this, the Microwave Applications Research Centre (MARC) was founded in early 1987 by the University of Wollongong, Illawarra Electricity and Industrial Microwave Applications (Aust.) Pty Ltd. (IMA) to develop applications for microwaves' unique heating characteristics. MARC has concentrated on industrial and commercial applications of microwave heating. The main areas of MARC's applied research and development have been or are as follows.

2.1.1 Heating/Pasteurisation/Sterilisation

The commercial process of heating, pasteurising or sterilising water based products such as sewage sludge on a pilot plant scale has been very successful. The ease and efficiency of selectively heating the product and the ability to contain the product in an microwave transparent material under pressure if required are currently being pursued. This process is subsequently reported.

2.1.2 Drying

Water is one of the best responding materials to microwaves. Microwave drying has been well researched and found to be very efficient in removing the last percentage of moisture. However, uneven processing known as "hot spots" can result with belt conveyor driers and MARC has developed a rotary microwave drier to minimise this problem.[1,2] Its concept is very exciting and testing to date has displayed excellent results with very even processing. The development of an improved commercial version is currently underway.

2.1.3 Chemistry

The theory usually used to explain the action of microwaves maintains that polar molecules such as water react to microwaves. Water molecules have an uneven distribution of electrical charge and attempt to rotate in a microwave field causing friction and heating. Electrically balanced or non polar molecules absorb little or no energy by this mechanism. This creates the possibility of selective promotion of reactions. There are many reported cases where productivity in rubber vulcanising, curing of urethene foam and hardening of polyester and epoxy resins has been increased several fold in commercial operations by microwaves.[3,4]

2.1.4 High Temperature Pyrometallurgy

Many of the materials used in the reduction of metals from ores are receptive to microwave energy. Some naturally occurring carbon materials are particular receptive and the most reactive are generally the low rank fuels not normally used as heating or reducing agents in pyrometallurgy. Both metallic oxide and sulphide ores can be receptive. However, magnetic iron ore or magnetite is particularly responsive.

The way in which these non-polar materials react to microwaves confirms that the polar rotation mechanism proposed for microwave heating is not the only energy transfer mechanism. The real explanation is obviously more complicated,[5,6] and the simplest way to rate materials' microwave power reception is its effective conductivity. Materials with increasing effective conductivity show greater power receptivity up to a point where the power absorption then falls to a low level for high conductivity metals. The form of the material and its temperature affect its conductivity and hence microwave receptivity. For example, glass is a poor receptor at low temperatures but a good receptor when melted.

MARC has concentrated its research work in the pyrometallurgical area where few other researchers appear to have ventured. Work so far has produced molten copper, iron, high alloy irons, lead, nickel and tin by microwave assisted and direct microwave smelting. Particular success to date include work on high intensity smelting with microwave precursor treatment which has achieved a process capable of producing 20 kilograms per hour of high grade tin.

A new project has recently started which has resulted from the above projects. The aim comprises of two parts, the first to use steelworks dusts to enhance sludge precipitation at sewage treatment plants and the second to dewater and dry this mixture and then smelt this dried mixture to produce iron using the residual sludge carbon content as the reductant.

2.1.5 Extraction/Reclamation

MARC has investigated microwave projects including extraction of gold from ores and concentrates, extraction and utilisation of rare earths, extraction of hydrocarbons from shale and reclamation of zinc from in-plant dusts.

2.1.6 Equipment

The conventional equipment used for microwave power applications has been the box oven similar to domestic ovens. In recent years, special shapes of ovens have appeared and for optimal efficiency, a microwave cavity or applicator specially designed for a particular application is generally required. MARC has investigated many cavity and applicator designs such as the rotary microwave drier, especially in higher temperature applications. MARC has also built its own power supply units (up to 6kW at 2450MHz) and is currently developing a 30kW 915MHz power supply.

2.2 Sterilisation, Disinfection & Pasteurisation - Definitions

The terms, sterilisation, disinfection and pasteurisation are widely used throughout this text hence their definition are given below,[7]

Sterilisation - A process that is intended to kill or remove all types of microorganisms, with an acceptably low probability of an organism surviving on any article.

Disinfection - A process that is intended to kill or remove pathogenic microorganisms with the exception of bacterial spores.

Pasteurisation - A process that kills non-sporing microorganisms by hot water or steam at 65 - 100°C

It is impossible to guarantee that every microorganism exposed to a particular treatment has been sterilised. It is therefore realistic to define sterilisation as a process that provides an acceptably low probability (e.g. one chance in a million) that a microorganism will survive the treatment.

2.3 Laboratory Scale Testing

In early 1986, the Water Board became aware of a 300kW microwave peat drier at Bombala in southern NSW. They approached IMA, the designer and manufacturer of the plant, to perform trials on the treatment of sewage sludge to hopefully pasteurise, or even sterilise, the material using microwaves.

Trials were run in which sludge was loaded onto an open weave belt and passed through the high powered oven. Although sludge was shown to be a very good receptor of microwave energy, the treatment method was unsuccessful.

The Board was not discouraged by this initial setback and decided to attempt to encapsulate the sludge in a closed microwave transparent container to allow processing at higher temperatures and also to subject the sludge to pressure treatment.

MARC was commissioned to investigate the overall potential of this approach and if this method of processing was successful, to design and develop a suitable processing plant.[8]

A series of bench tests on open vessel and pressure-cooked sludge samples (using a domestic microwave oven pressure cooker) indicated that only those samples pressure-cooked for a minimum of 10 minutes reached the appropriate level of sterilisation.

The conclusion drawn from this testing was that sterilisation of sewage sludge using a pressurised microwave heating process was feasible and would require maintaining a sludge temperature of at least 120^{o}C at 150kPa gauge for at least 10 minutes.

2.4 Initial Microwave Treatment Plant

A semi continuous pilot scale microwave heating and pressure treatment system was designed by MARC for continuous 'pressure cooking' of sewage sludge.[8] Trials with this unit were conducted at MARC's Industrial Laboratory located at Coniston, (Figure 2.1 & Photo 2.1 & 2.2).

The features of the equipment include

Feed pump - 50mm mono pump with variable speed drive,

Delivery pipe - 100mm diameter pyrex pipe 3 metres long,

Microwave power - Variable 40kW microwave power supply,

Collection chamber - Pressurised holding vessel incorporating a non return valve.

In this test unit the temperature of the sludge was measured by a thermocouple attached to the discharge pipe about 1.3 metres down stream from the cavity. The collection chamber was pressurised to around 150kPa (gauge) by an air compressor. Sludge was pumped into the processing pipe by a mono pump with microwave power applied as the sludge passed through the glass processing pipe in the cavity.

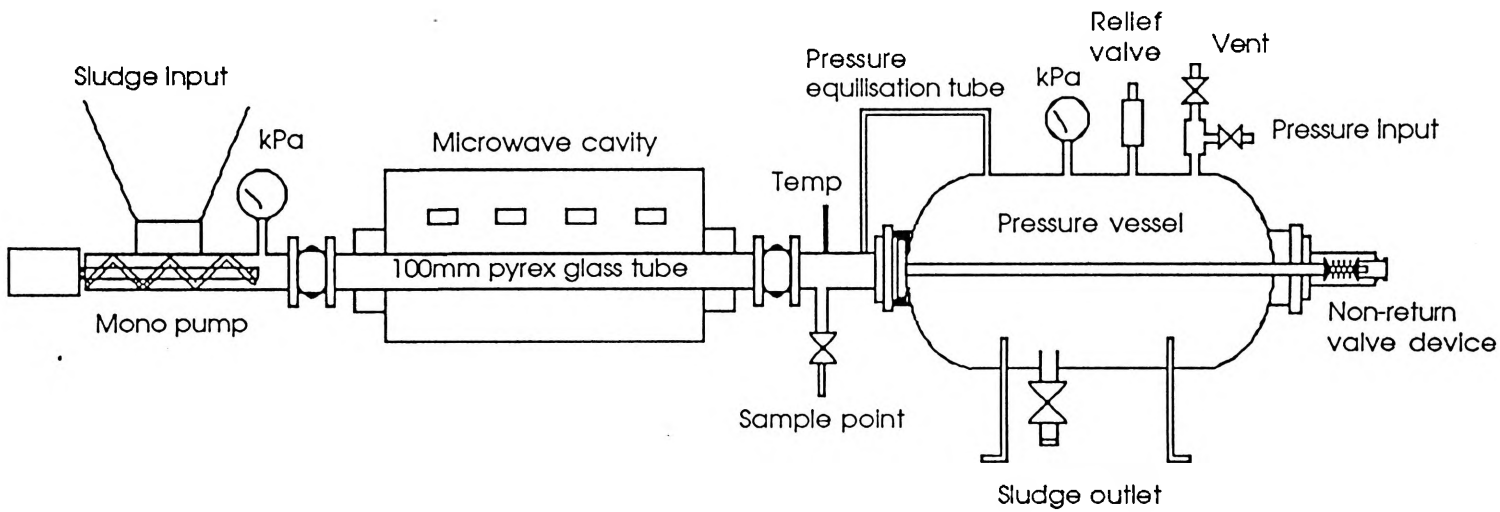


Figure 2.1 Schematic of initial microwave heating and pressure treatment plant.

The system reached operating temperature and pressure after 10 minutes and was then monitored to ensure the pressure did not exceed 150kPa. Steam pressure build up was rapid, indicating adequate microwave power for the volume of sludge passing through the cavity.

Excessive pressure build up in the chamber generated by heating the sludge was vented to the atmosphere via a pressure relief valve. The testing was carried out over three hours with the equipment operating more or less continuously. The parameters and results of the tests are as shown in Tables 2.1 & 2.2. The sludge samples were taken at various temperatures and were tested by the Board's biological testing laboratory.

Table 2.1 Parameters of Initial Microwave Processing Plant

Processing time in cavity	7.8 minutes approx.
Processing time to sampling point	10 minutes approx.
Mass flow rate	140kg/ hr approx.
Microwave power	27kW
Total plant power	52kW

Table 2.2 Results of Initial Microwave Processing Plant

Sample	Temperature	E. coli	Total Bacteria
Untreated	20°C	>>10	10^8
1	107°C	0.2	10^4
2	108°C	0	10^4
3	115°C	0	10^1
4	119°C	0	<10
5	121°C	0	<10

These results confirmed earlier results that a combination of microwave heating and pressure treatment can successfully sterilise sewage sludge using a pilot scale semi-continuous process.

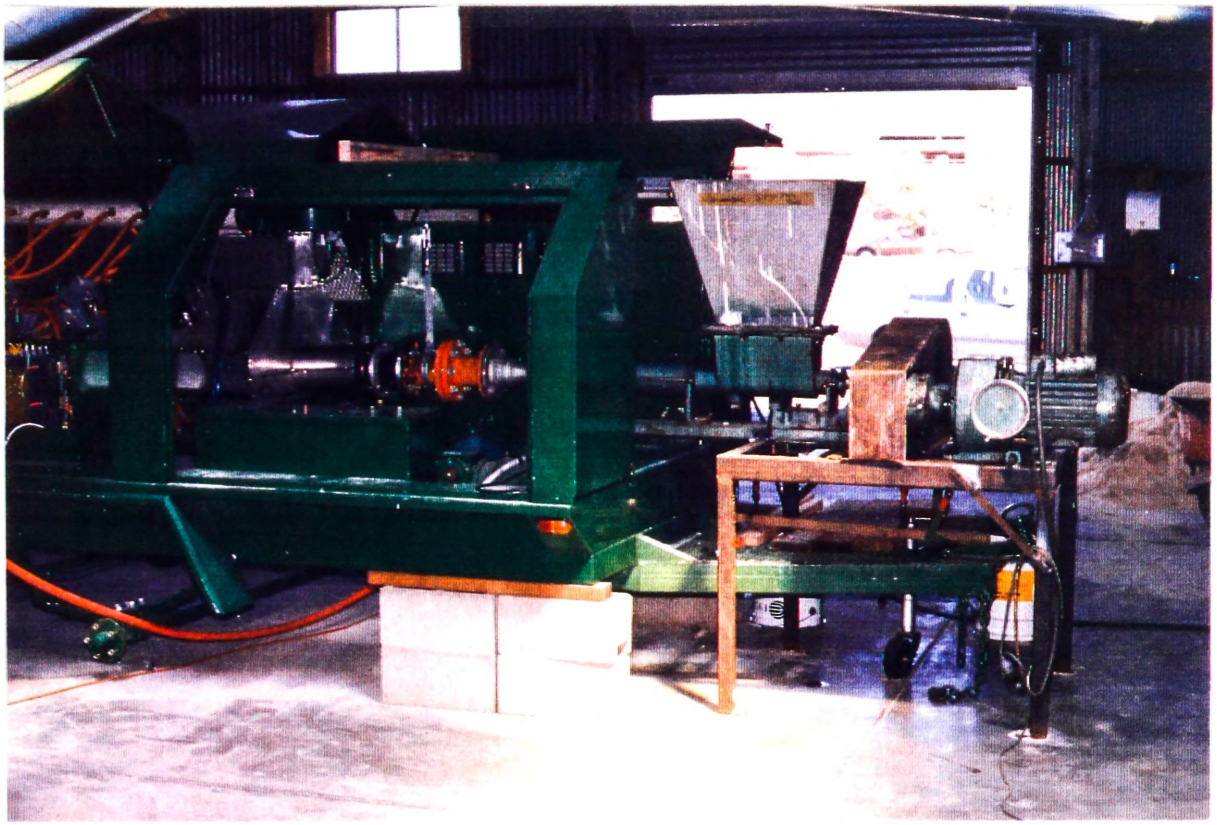


Photo 2.1 Inlet arrangement showing mono pump and part of microwave cavity.

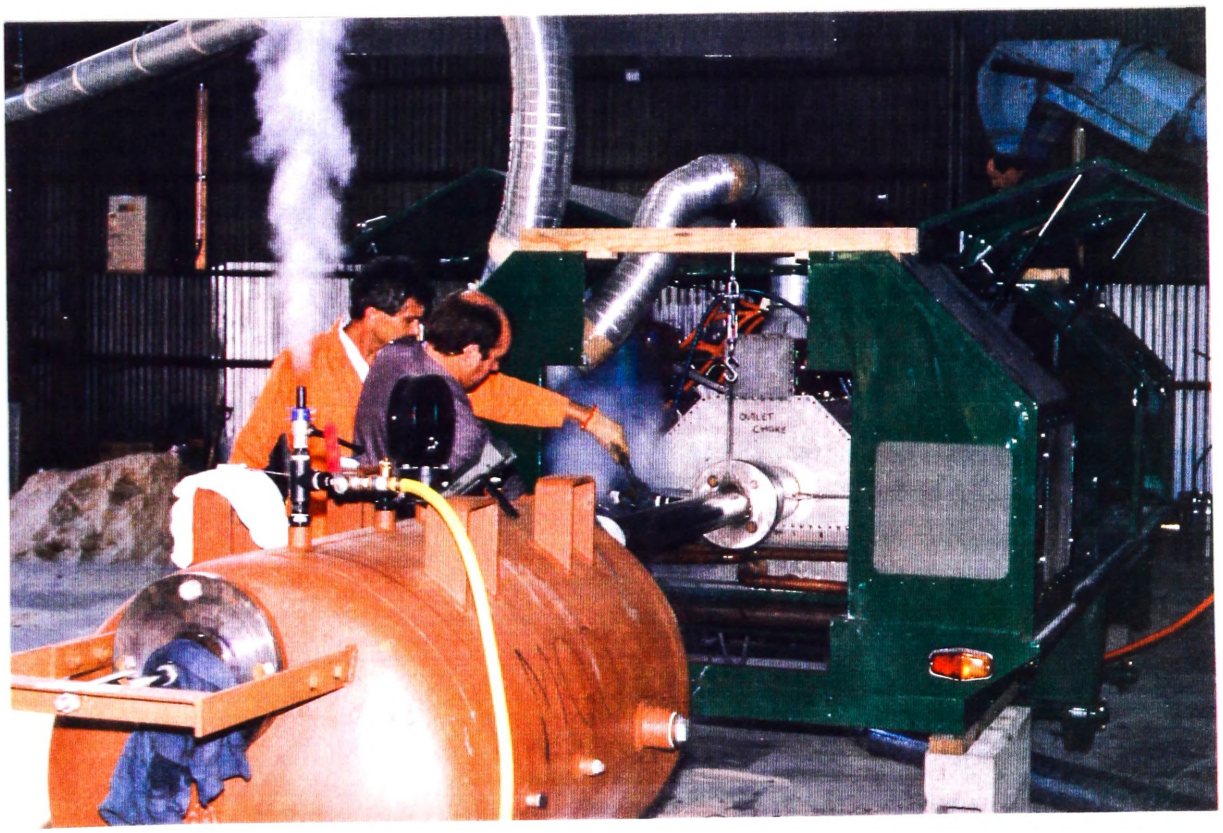


Photo 2.2 The exit arrangement showing pressure vessel in foreground and microwave unit in the background.

3. Literature Review

3. Literature Review

3.1 Sludge Overview

The following literature review on sewage sludge has been sourced from references (9), (10), (11) & (12).

Sludge is one of those onomatopoeic words which people love to hate. It conjures up images of an unwelcome evil ooze. Unfortunately sludge is also the principal and inevitable by-product of sewage treatment. True to its name, it is difficult to handle and carries some very unpleasant biological agents such as pathogenic bacteria, viruses, protozoa and helminth ova and sometimes unpleasant toxic materials such as lead, cadmium, mercury and organochlorines.

3.1.1 Sludge Quantities

The Water Board operates 36 sewerage treatment plants (STP) which treat the sewage from a population of about 3.6 million persons in the Sydney, Blue Mountains & Illawarra areas. Sewage sludge is the settled material collected at each of the plants.

About 6 million litres of liquid sludge, equivalent to 120 dry tonnes of solids (DTS), are collected each day. The quantity of sludge collected depends upon the effectiveness of solids capture. Nearly two thirds of this sludge is collected at the major coastal plants - Bondi, Malabar & North Head. With the exception of North Head, where raw sludge is incinerated, sludge is anaerobically digested prior to discharge to the ocean or storage lagoon. Since October 1989, lagooned sludge from inland and minor coastal plants have been composted or applied directly to land.

In March, 1989 the N.S.W Minister for the Environment directed the Water Board to cease ocean disposal of sludge by 1993 or sooner. The quantities and projected forecasts of sludge collected and present treatment methods are detailed in Table 3.1.

Table 3.1 Quantities & Treatment

Plant	Estimated Sludge Quantities Collected and Forecast (DST/Day)			Current Treatment
	Current	October 1992	October 1996	
Major Ocean Plants				
Malabar	63.3	70-120	105-125	P,D
Bondi	8.5	10-20	20-25	P,D,Dw
North Head	9.6	26-60	60-70	P,Dw
Minor Ocean Plants				
Cronulla	3.8	4.4	5.0	P,D,Dw
Warriewood	1.4	1.7	2.1	S,D,L,Dw
Inland Plants				
Castle Hill	0.6	0.75	0.9	T,D,L
Glenfield	4.0	4.9	5.8	T,D,L,Dw
Hornsby Heights	0.7	1.1	1.5	T,D,L
Kellyville	0.07	0.08	1.2	T,L
Liverpool	1.4	1.8	2.2	T,D,L,D
North Richmond	0.14	0.3	0.5	T,L
Penrith	3.5	4.4	5.3	T,D,L,Dw
Quaker's Hill	4.8	6-8	7-9	T,D,L,Dw
Richmond	0.3	0.3	0.3	T,D,L
Riverstone	0.2	0.7	1.2	T,D,L
Round Corner	0.03	0.04	0.05	T
St. Mary's	4.9	5-8	6-9	T,D,L,Dw
Warragamba	0.06	0.06	0.07	S,D,D
West Camden	0.8	1.3	1.8	T,L
West Hornsby	1.3	1.4	1.7	T,D,L,Dw

Table 3.1 Quantities & Treatment
(ctd...)

Plant	Estimated Sludge Quantities Collected and Forecast (DST/Day)			Current Treatment
	Current	October 1992	October 1996	
Blue Mountains				
Blackheath	0.08	0.09	0.1	S,D,Db
Glenbrook	0.5	0.55	0.6	T,D,L
Hazelbrook	0.2	0.21	0.26	S,D
Mount Riverview	0.16	0.18	0.2	T,D,Db
North Katoomba	0.05	0.07	0.09	S,D,Db
South Katoomba	0.26	0.26	0.26	S,D,Db
Valley Heights	0.16	0.18	-	S,L
Wentworth Falls	0.37	0.42	0.5	S,D,L
Winmalee	0.4	0.5	1.0	T,L
Mount Victoria	0.01	0.01	0.02	S,L
Illawarra				
Bellambi	2.5	2.6	2.8	P,D,Db
Bombo	0.35	0.37	0.5	S,L
Port Kembla	1.4	1.4	1.4	P,D,Dw
Shellharbour	1.4	1.7	2.0	S,D,L,Dw
Wollongong	2.3	2.4	2.6	S,D,Dw

P = primary treatment, S = secondary, T = tertiary, L = lagoons onsite, D = digestion tanks, Dw = permanent dewatered equipment installed or planned, Db = sludge drying beds.

3.1.2 Sludge Quality

The typical composition of digested sludge is shown in Table 3.2. The organic material and plant nutrients can make it useful as a soil conditioner or low grade fertiliser.

Table 3.2 Typical Composition of Digested Sludge

Component	Range (% TDS)	Typical (% TDS)
Volatile Solids	30 - 60	40
Grease and Fats	5 - 20	-
Protein	15 - 20	18
Nitrogen (N)	1.6 - 6	4.0
Phosphorous (P_2O_5)	1.5 - 4	2.5
Potassium (K_2O)	0 - 3.0	1.0
Cellulose	8 - 15	10.0
Iron	3 - 8	4.0
Silica	10 - 20	-

Note TDS = Total dry solids usually in the range 2 - 4% ex-digestor, increasing up to a maximum 12% in lagoon however typically 8%, pH of sludge is about 7, alkalinity typically (as $CaCO_3$) is about 3000mg/l, organic acids about 200mg/l (as HAc) and thermal value about 9MJ/kg.

3.1.3 Sludge Use/Disposal Technologies

Achievement of the Water Board's objectives of ceasing ocean disposal by 1993 and fostering beneficial uses of sludge depend upon the identification of strategies which are appropriate in terms of costs, implementation time frame, practicality and environmental impact. Factors to be considered in this process include:

- nature and location of the STP,
- availability of local opportunities to use/dispose of sludge,
- cost-effectiveness of alternative technologies with regard to size of the plant, environmental impact of the operation,
- chemical contaminants present in the sludge and the prevailing guidelines on sludge use.

Apart from encouraging the land application of sludge products, several new processes are also being investigated by the Board. Existing and developing technologies being investigated are as follows:

3.1.3.1 Land Application

Liquid and dewatered sludges are commonly applied to agriculture and reclamation sites in the United States and Europe. Increased restrictions are being applied to avoid adverse affects especially from chemical contaminants and pathogens. Land reclamation enables large quantities of sludge to be used however applications are generally once-off.

3.1.3.2 Composting

Composting is well established in the United States as a method to produce a stable, marketable product. Either digested or raw sludges may be used. After dewatering the sludge is mixed with a bulking agent such as wood chips and/or saw dust and composted by either a static pile, windrow or in-vessel system.

Raw sludge composting may become more commonplace in the future. This is a direct alternative to sludge digestion at the STP.

In the United States a large number of large scale facilities compost sludge on a continuous basis. Reports from independent observers suggest that many are less than successful in terms of odour, emissions and the product quality. Apparently, plant designs focus upon materials handling rather than optimising the composting process.

3.1.3.3 Heat Drying

Heat drying to produce fertiliser is now more widely used, especially in the United States. In Adelaide (South Australia) dried sludge is used to produce a base material for several fertiliser products. More energy efficient dryers are now available. However costs generally exceed those of composting. Local markets for heat dried sludge remain to be properly quantified.

3.1.3.4 Pasteurisation

Pasteurisation can be achieved by several methods including submerged combustion, microwaving and heat exchangers. Experience in Switzerland has shown that pre-digestion pasteurisation minimises reinfection of pathogens and will be discussed later. Microwave pasteurisation and sterilisation has been trialled at Shellharbour STP, details of which are to be discussed shortly.

3.1.3.5 Oil from Sludge

An oil from sludge pilot plant has been trialled at Malabar STP. Sludge is destroyed by a thermo-chemical process, similar to pyrolysis and produces a product equivalent to diesel fuel and solid char. The combustion of the char and waste gas produces heat for the process.

3.1.3.6 Deep Well Aqueous Phase Oxidation

Digested sludge is pumped into concentric tubes to a depth of 1.5 kilometres where high pressure and temperature conditions oxidise the sludge to produce an ash, very dilute acetic acid and waste gases. The effluent may then be scrubbed to remove ammonia if it presents a problem. Stainless steel pipes are used to minimise corrosion and the pipes can be replaced in the future, when required. Heavy metals are reported to be bound in the ash which may be disposed of by use in bricks or road base.

3.1.3.7 Incineration

The Board has held discussions with several companies to determine the environmental acceptability and cost of incinerators. Available advice indicates that emission control equipment is available to enable the burning of sludge containing heavy metals and toxic organic compounds. Opportunities also exist to recover waste heat and ash for beneficial purposes. Preliminary cost data suggests that incineration is generally the most expensive option. It is also receiving much opposition from environmentalists and it is unlikely to become common practice in Australia.

3.1.3.8 Smelting of Sewage Sludge and Steelworks Dusts

Work is currently underway to develop and evaluate a smelter which can take a dried mixture of sewage sludge and steelworks dusts (a waste product from the steel making industry) and smelt the two together to produce iron. Preliminary runs in an induction furnace have proved successful. The iron product can absorb traces of heavy metals without harmful effect, whilst the high temperatures of smelting can break down any noxious chemicals in the gases produced. Volatile metals, such as zinc, mercury and cadmium, can be condensed out of the furnace gases.

3.1.3.9 Brick Project

Dried sludge is ground into a powder, mixed with fly ash (a waste product from the coal fired power generating plants) and a slurry made from shale or clay, formed into bricks and then fired. During the firing process, the sludge burns and therefore the amount of fuel required is significantly reduced.

Any toxins in the sludge are sealed permanently in the brick. The project aims are to market an economical brick which is attractive to the users.

3.1.4 Regulations and Guidelines

Guidelines for sewage sludge disposal and use are required to control environmental and public health impacts of disposal and use practices. There are three authorities with an interest in placing controls on sludge disposal in New South Wales. These are the Department of Health on public health grounds, NSW Agriculture and Fisheries on quality of agricultural products arising from the use of sludge and the State Pollution Control Commission (SPCC) on environmental grounds.

3.1.4.1 Department of Health

The Department is responsible for monitoring and controlling the spread of notifiable infectious diseases in the community. In 1987 it issued draft guidelines for the use of domestic sewage sludge.[13] However, the department's guidelines have been revised to closely reflect regulations proposed in February 1989, by the United States Environmental Protection Agency (USEPA).[14]

3.1.4.2 NSW Agriculture and Fisheries

This organisation is currently producing guidelines for the agricultural use of sewage sludge, addressing such topics as heavy metal accumulation in the soil and cropping practices. SPCC and Health Department requirements for the agricultural use of sludge will also be included.

3.1.4.3 State Pollution Control Commission

The SPCC does not have specific guidelines for sludge disposal, although the Clean Waters Act 1970, the Clean Air Act 1961 and their respective Regulations implicitly require effective controls on the storage, treatment and disposal of sludge.

3.1.4.4 Other Australian States

Table 3.3 summarises sludge disposal and reuse practices in each Australian state and lists the main points from their respective disposal guidelines.

Table 3.3 Summary of Interstate Practises and Guidelines for Sludge Disposal and Use

STATE	DISPOSAL PRACTICES	GUIDELINES
VICTORIA	Melbourne & Metropolitan Board of Works Stockpiling, landfilling on site, composting trials underway.	Health Department of Victoria Condition of sludge re-use depend on sludge age. (a) Up to 2 years - only for "seeding" at other plants or landfill or application on site. (b) Dried, 2 to 7 years old - subject to specific approval, can be used on municipal parks and gardens or as landfill. (c) Dried, over 7 year-no restrictions. (d) Sterilised - rotary kiln min 120^{o}C inlet - 240^{o}C outlet for > 60 minutes, no restrictions.
QUEENSLAND	Brisbane City Council Anaerobically digested, dried mechanically or on beds, landfill, or soil conditioner after withdrawing and stockpiling for > 1 year.	Queensland Department of Health Requires stockpiling of sludge for > 12 months prior to reuse, to reduce pathogen levels.

Table 3.3 Summary of Interstate Practises and Guidelines for Sludge Disposal and Use (ctd...)

STATE	DISPOSAL PRACTICES	GUIDELINES
SOUTH AUSTRALIA	Engineering & Water Supply Department Dried sludge from Bolivar and Christies Beach purchased by contractor, sterilised and sold for use in fertilisers and soil conditioners. Digested sludge from Glenelg Port Adelaide discharged to St Vincents Gulf with likely adverse environmental effects From other plants dewatered sludge to landfill or mine rehabilitation.	SA Department of Health Requires heat sterilisation of sludge for unrestricted use, ie. rotary kiln 120°C outlet for 1 hour. Use of unsterilised sludge not covered by specific legislation except prohibition of use on pasture used for cattle or pig grazing. SA Central Board of Health Has statutory responsibility for disposal of sewage sludge.
WESTERN AUSTRALIA	Water Authority of WA Dewatered and incinerated (ash buried onsite) or sold to contractor for soil conditioning.	Health Department of WA Only regulates septic tank wastes. Water Authority of WA No regulations on use of dried sludge ex treatment plants.

Table 3.3 Summary of Interstate Practises and Guidelines for Sludge Disposal and Use (ctd...)

STATE	DISPOSAL PRACTICES	GUIDELINES
NORTHERN TERRITORY	Power and Water Authority Lime stabilised sludge used for land reclamation of mangrove swamp. Incineration has been discontinued because of high cost.	No requirements.
TASMANIA	Hobart City Council Glasshouse bed dried, used as soil conditioner on Council's parks & gardens or to landfill.	Department of Health Services, Tasmania Sludge is defined as "sludge from an STP which has been thoroughly digested and dried". Only sludge which has been held > 2 years can be used. Not to be used in vegetable gardens, orchards, sportsgrounds or nature strips. To be immediately ploughed in, and kept damp till vegetation established.

Table 3.3 Summary of Interstate Practises and Guidelines for Sludge Disposal and Use (ctd...)

STATE	DISPOSAL PRACTICES	GUIDELINES
NEW SOUTH WALES	Water Board Major portion digested and shoreline discharge or incinerated. Minor portion digested, dewatered and composted or buried on site.	Department of Health,NSW (Draft Guidelines, 1987) Prior to use, sludge to be stabilised by digestion, extended aeration, lime stabilisation or equivalent, then stored for minimum of 12 months or composted at > 40^{o}C for 5 days. Suitable for forest areas, rehabilitation of mining quarrying or roadworks, turf farms and agricultural purposes. For unrestricted commercial use, additional heat treatment or composting required.
	Hunter Water Board Main plants do not separate sludge. Raw sewage screened and discharge to shoreline. At other plants, sludge lagooned and disposed to land on site.	
	Country Centres (Council operated) Digested, lagooned & dewatered in drying beds or mechanically. Usually used as landfill on or near site. Isolated cases of land application to pastures and composting.	

3.1.5 Overseas Regulations

A summary of overseas regulations and guidelines on the control of pathogens is shown in Table 3.4.[15]

Table 3.4 Overseas Regulations or Guidelines - Summary

Country	Control of Pathogens
USA (Federal Regulations)	Treatment by "Process to Significantly Reduce Pathogens" before applying to land. Treatment by "Process to Further Reduce Pathogens" for growing of food chain crops.
United Kingdom (Guidelines)	Restraints on usage for 11 sludge categories ranging from raw sludge to full treated. Raw sludge only for production of animal feed and food crops to be cooked. On pasture, 6 months delay for untreated sludge and 3 weeks delay for treated sludge.
West Germany (Regulations)	Mandatory code of practice for "Epidemically and Hygienically Harmless Land Disposal of Sludges". Restricted usage for air dried digested sludge. Preference for heat treatment of sludge.
European Economic Community (Regulations)	Untreated sludge may only be used if it is injected or worked into the soil. Otherwise sludge shall be treated before being used in agriculture. Restricted usage of air dried digested sludges. Preference for heat treatment of sludge.
South Africa (Guidelines)	Limited usage of digested sludge for crops not eaten raw by humans and for fodder crops. Air dried (90 days) digested sludge permitted on non-vegetable crops if well mixed with soil.

3.2 Microwave Technology

3.2.1 History

Microwave energy has been used in industrial processing for many years. Its adoption against competition from more conventional heating methods has been its appeal of special advantages, such as selective heating, processing speed and efficiency. In the early stages of the evolution of microwave heating these advantages were often difficult to justify against the relative cheapness of fossil fuel heat. This, together with the natural reticence of many industrialists to change existing but often inefficient and obsolete conventional systems, has resulted in the slow growth of the microwave heating industry. The 1960's were primarily characterised by the obstinate opportunism of many newly formed manufacturers of microwave equipment to capitalise during an era of economic expansion but who unfortunately did not possess the technical expertise and after sales service necessary to ensure customer satisfaction.[16]

After the failures of these early endeavors, these trends were slowly reversed during the seventies following a determined effort to form design teams having the necessary wide range of professional engineering capability and to provide an appropriate after sales service. The disappearance from the scene of many of the initial firms consolidated the remainder of the field.

In the early eighties, the domestic microwave oven revolutionised the kitchen and now in the 1990's has become standard equipment in most homes. This acceptance, along with the development of more reliable equipment and better utilisation of the technology, has led to a greater use of microwaves in industry.

3.2.2 Advantages of Microwave Energy

Some of the well established advantages of microwave energy over conventional techniques are well documented and outlined below;[17]

- Selective energy absorption by microwave receptive constituents,
- Heat transfer is independent of the medium,
- Preferential internal heating in some products,
- Greater efficiency especially in the falling rate period of a drying curve,
- Speed of heating can greatly reduce process times,
- Energy is transferred in a clean manner,
- Power can be instantaneously controlled,
- More compact systems,
- Friendlier to the environment.

3.2.3 Industrial Applications

3.2.3.1 Food and Beverage Industry

A current literature review shows a marked increase in the number of industrial installations for the last decade, especially in the food and beverage industry. There are many successful commercial applications in this industry and these are summarised in Table 3.5.

Table 3.5 Summary of Microwave Processes in the Food and Beverage Industry.[18]

Process	Process Description	Foods Processed
Baking	- Microwaves plus thermal energy.	- Biscuits, bread.
	- Microwave/hot-air systems.	- Bread crumbs, doughnuts.
Blanching	- Microwaves at 2450MHz with continuous dehydrator or forced freeze-air cooling, followed by steam finishing.	- Mushrooms for canning, corn, potatoes, fruit, spinach or other vegetables.
Doughnut Frying	- Microwaves heat only exposed dough riding on hot fat.	- Doughnuts.
Doughnut Proofing	- Continuous proofer with 2 heating stages and intermediate resting stage.	- Doughnuts.
Drying	- Microwaves, hot air, continuous humidity control.	- Pasta, egg yolk powder, dry milk for babies, onions tomato paste, rice cakes, snack food, seaweed, bacon bits.
Freeze-Drying	- Combination of infrared and microwave heaters.	- Coffee.
	- Microwaves used to accelerate drying and provide conditions needed for the compression of certain foods whose moisture content is less than 20%.	- Beef slices,vegetable pieces, fruit, mushrooms, chicken, shrimp, lobster fish slices.
Meat Emulsions	- Emulsion pumped through microwave tubes in microwave cavity for small diameter links; for large diameter sausage links, emulsion pumped through circular waveguides.	- Sausage.
Oyster Opening	- Microwaves cause self gapping of oyster shells without cutting.	- Oysters.

Table 3.5 Summary of Microwave Processes in the Food and Beverage Industry.[18] (ctd...)

Process	Process Description	Foods Processed
Pasteurisation (inactivate vegetative microbes)	- Process sliced bread in packages within cardboard.	- Sliced bread.
	- Temperature raised from 20-80°C - Size graded and lye peeled, trimmed, blanched vacuum packaged, pasteurised; raw or cooked product possible.	- Speciality bread. - Potatoes.
	- Multitherm continuous process for pasteurisation and/or sterilisation; formfill-sealed packaged foods vacuumised during packaging, then preheated in water to 80°C, over-pressure then microwaves applied while submerged in water; product cooled to room temperature then dried.	- Meat, fish, shellfish precooked foods,fruits, vegetables, salads, all formfill-seal packages.
	- Archilles process; food fed to plastic tube at high speed in heat treatment zone under water, tube conveys heat to liquid, then cooled, sterilisation temperature typically 155°C, pouch then formed.	- Liquids and liquid foods.
Precooking	- Microwaves, steam and/or oil browning.	- Meat patties.
	- Chicken breasts and thighs separated from legs and wings.	- Chicken.
	- Steam hot air, microwaves.	- Bacon.
	- Microwaves, hot air.	- Bacon bits.
	- Microwave precooked in can then sealed.	- Bacon bits, fish, sausage links and patties, potatoes.
Puffing	- Puffing and drying.	- Preserved marine products snack food, rice cakes, seaweed, egg yolks, vegetables, fruit products.
Rendering	- Microwaves.	- Fats, tallow.

Table 3.5 Summary of Microwave Processes in the Food and Beverage Industry.[18] (ctd...)

Process	Process Description	Foods Processed
Roasting	- Microwaves plus infrared waves for browning afterwards. - Hot air then microwave heating, causing fat in nuts to liquify, then sliced easily.	- Fish, meat. - Nuts: eg, almonds, cashews peanuts. - Cocao, coffee beans. - Lavera-Japanese seaweed food.
Sterilisation (inactivate microbial spores)	- Arhilles process for liquids and liquid foods. Multitherm process: pouches pass through liquid baths to about 80°C, microwave heated under pressure to to approximately 131°C, then cooled to 90°C and dried.	- Liquid or semiliquid products: eg, milk. - Form-fill-seal packages: eg, fruit, vegetables, salads, meat, fish, shellfish, precooked foods. - Fish,vegetables, fruit, pouch-packaged foods, wrapped marine products, desiccated coconut.
Tempering (raise temp to below freezing point)	- Semi-thawing. - At 2450MHz food removed from package, unlike at 915MHz.	- Poultry. - Steak, fish, ham,lamb, berries, meat patties, butter.
Vacuum Drying	- Microwave process in vacuum, foam produced by rapid evacuation of water, later becomes dry meringue (instantly soluble flakes or powders usually produced. - Partial vacuum of 3.4-6.6kPa to permit moisture evaporation, moisture condensation inner chamber wall and drains into condensate tank.	- Fruit juice concentrate becomes powder. - Grains: eg, wheat, rice, rye soybeans - Cottonseed,yeast,peanuts, pecans,corn, fruit, tomatoes peppers, seasoning,protein preparations, meat extracts plant and gland extracts, instantly soluble vegetable powders.

3.2.3.2 Non-Food or Beverage Industries

Industrial microwave processes outside the food and beverage industry are not as wide spread and even fewer have enjoyed the commercial success associated with the food and beverage industry. However, there are a lot of interesting and promising laboratory and pilot installations reported and currently under trial so this poor commercial trend could change in the future. Table 3.6 summarises current reported industrial microwave installations.

Table 3.6 Summary of Industrial Microwave Process
(Non-food or Beverage Industries)

Process	Material/Process
Curing/Hardening	Polyvinylchloride belts and pipes, urethane foam, polyester, epoxy resin, foundry cores.
Drying	*Atmospheric, fluidised bed, or spray drying* Paper, film, printing ink, paint laquer, casting moulds, plastic coatings, lumber adhesives, pharmaceutical (fluidised) pastes and washes (foundry), photographic silver halide coatings, leather, vitamins, nuts, slip cast crucibles, textiles, molasses. *Vacuum drying* Harvested crops.
Heating	Polyurethane foam, tobacco, high nitride reforms, cigarettes blood, press-setting in pencils, plasmas.
Melting	Refractory dielectrics (oxides), dewaxing in investment castings.
Sterilisation	Japanese straw mats.
Vulcanisation (curing)	Natural or synthetic products (extruded blanks, tyres, bales, injection moulded), elastomers and foams.

3.3 Review of Related Pasteurisation Work

A review of related work on sludge pasteurisation shows a lot of work has been conducted in Switzerland. Germany and the Nertherlands are also using this technology.[19]

Switzerland, with its predominantly intensive agricultural systems and because of its long and proud tradition in dairy farming, became vanguard in recommendations to introduce measures for reducing the risks attached to sludge disposal on land. Towards the end of 1971, regulations were imposed which prescribed that sewage sludge which was to be applied to grazing and fodder land during vegetation season had to be disinfected. The system adopted was invariably pasteurisation after anaerobic digestion. Disinfection was carried out in the sewage treatment plant in a separate operation following sludge stabilisation; generally using anaerobic methanogenic digestion.

Within six years of introduction of these regulations, one in eight plants, (about 70 plants in total), had been equipped with relative pasteurisation systems. Some two or three years after the introduction of these measures, skepticism arose, particularly in veterinary circles, concerning the efficiency of the manner in which pasteurisation was effected.

The Federal Department for the Protection of the Environment instigated a survey and close examination of a cross-section of pasteurisation plants. It found that in a large majority of cases, recontamination of the pasteurised sludge occurred mainly in subsequent stockpiling or in some cases due to bad design within the pasteurisation process itself.

The investigation pointed out that solely heating sludge to 70°C for the duration of 30 minutes was itself insufficient to guarantee a reasonable period of immunisation against reinfection. It also reported although not conclusive, thermal treatment altered the structure of the sludge in such a way that a hospitable environment was established for pathogens if reinfection did occur.

Apart from bad engineering design, process errors and untrained operators, it was found that the cost of the required energy became excessively high, especially for plants which could utilise only little or no digestor gas and that not one plant incorporated heat recovery. As a result, the Federal Department for the Protection of the Environment freed local sewage plants in April 1977 from the obligations to pasteurise their sludge, pending new regulations.

It was realised that by improvements to design, installation and operation, the required disinfection could be achieved with the existing pasteurisation systems. However, the problem of subsequent stockpiling of the sludge in a hygienic condition could only be achieved if a change in the sequence of contempory sewage sludge treatment was undertaken. The so-called "post-pasteurisation" involving the sequence,

Stabilisation (digestion) - Pasteurisation - Stockpiling,

could not provide a reliable process for disinfection.

Early studies in the behavior of pathogens under aerobic methogenic surroundings, indicated that if sludge was pasteurised before stabilisation, the uncontrollable proliferation of pathogens was restricted and as a function of time the number of pathogens reduced.

With this in mind, it was considered that by pasteurisation of raw sludge, the matter or substance released by alteration of the sludge structure due to thermal treatment would be decomposed in the following anaerobic digestion stage and so called "pre-pasteurisation" was proposed,

Pasteurisation - Stabilisation (digestion) - Stockpiling.

In an extended series of preliminary tests, indications were that pre-pasteurisation was considered to increase hygienic storage life of sludge and offer adequate protection against the transfer of pathogens to agriculture.

Pre-pasteurisation did however give rise to several new problems,

- Twice the volume of sludge would have to be treated and hence a considerable rise in energy consumption was needed.
- The pasteurisation would have to operate all year round to adjust with the daily and seasonal volume changes of sludge as compared with batch pasteurisation carried out only during the vegetation season.
- The old plants would have to be refurbished or replaced and the new process would need to incorporate efficient heat recovery systems.

The process incorporating heat recovery ideally visualised was that following pasteurisation, the sludge could be cooled down in a heat exchanger system, thereby preheating the incoming, untreated (cold) sludge. The cooled but still warm pasteurised sludge would be feed into the digestor, its latent heat serving to cover the heat loss of the digestor. The preheated, untreated sludge would be raised to pasteurisation temperature in a separate process.

In the majority of cases it should then theoretically be possible to maintain the operation temperature of the heated digestor solely by feeding in warm pasteurised sludge without the necessity for separate heating of the digestor content, as normally occurs. This would then substantially reduce the energy demand and the total heat requirement for pasteurisation being practically fully recovered and transferred to the digestor.

In 1978 a range of companies were invited to develop new disinfection systems with particular attention to the energy problem presented. The systems developed were reported in a workshop on "Disinfection of Sewage Sludge: Technical Economic and Microbiological Aspects," held in Zurich in May 1982.[19] In this, the most recent reference available, there are essentially two acceptable processes described; thermal pre-pasteurisation and aerobic thermophilic digestion which are both outlined below. In May 1981, a Swiss Order became enforced prohibiting post-pasteurisation of sewage sludge on health grounds and also among other things, sewage treatment plants with sludge disposal to other than arable land must be in a position to effect sludge disinfection by 1990.

Elsewhere overseas, the United States EPA recently released regulations in February 1989,[14] proposing that post pasteurisation of sludge can be performed if there is an additional process to inhibit recontamination. This inhibiting process may be dryness, presence of certain chemicals or presence of vegetative bacteria.

3.3.1 Thermal Pre-pasteurisation

This process entails pasteurisation and conditioning untreated sludge prior to digestion incorporating heat recovery. Since almost all the heat generated is recovered, the process achieves optimum energy efficiency and low operating costs with no recontamination.

Literature indicates that in the early 1980's, several manufacturers were trialling plants and marketing this technology with the results proving very successful. An outline of a typical plant process is outlined below in reference with Figure 3.1.

Pump P1 continually (or intermittently if the unit includes a buffer stack) draws sludge from the pre-thickener, through the comminutor and into the counterflow heat exchanger I, where it is heated to 70°C by the circulation of hot water. From there the hot sludge is passed on to a storage tank with three compartments; one for filling, one for storage and the other for emptying - each operating continuously in a 30 minute cycle.

Once the sludge has been pasteurised, pump P2 pumps it through heat exchanger II, where the sludge is recooled by the circulating water to about 40°C before it enters the digestor. In this process the circulating water is reheated to about 60°C before proceeding to the boiler for further heating to a maximum temperature of between 85°C and 90°C.

The recooled sludge is continuously admixed with the sludge circulating in the digestor, the inlet temperature being chosen to cover the heat loss from the digestor typically between 35 and 45°C.

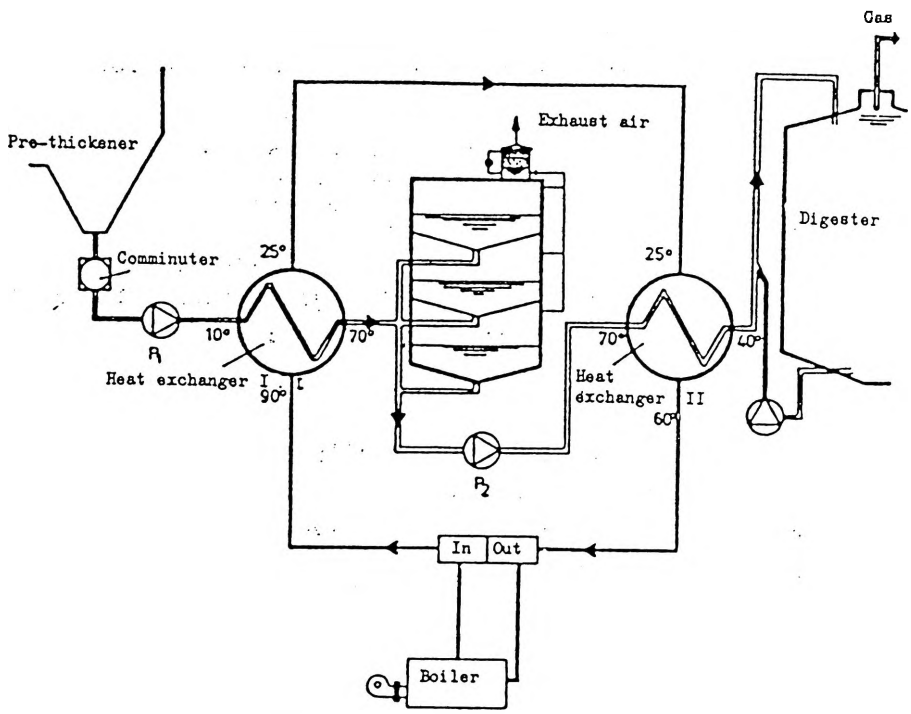


Figure 3.1 Schematic of a typical Thermal Sludge Treatment Process[19]

3.3.2 Aerobic Thermophilic Process

This process was developed from principals in the field of biotechnology and with the support gained during the development of the thermal pre-pasteurisation process. It is similar to the pre-pasteurisation process, although the storage tank or reactor is aerated by a mixture of oxygen, oxygen and air, or air (Figure 3.2). Again, in the early 1980's, several manufacturers were trialling plants and marketing this technology. Advantages of this process over thermophilic process are,

- Digested sludge exhibits superior thickening properties.
- Retention time of sludge in the digestor can be more than halved.

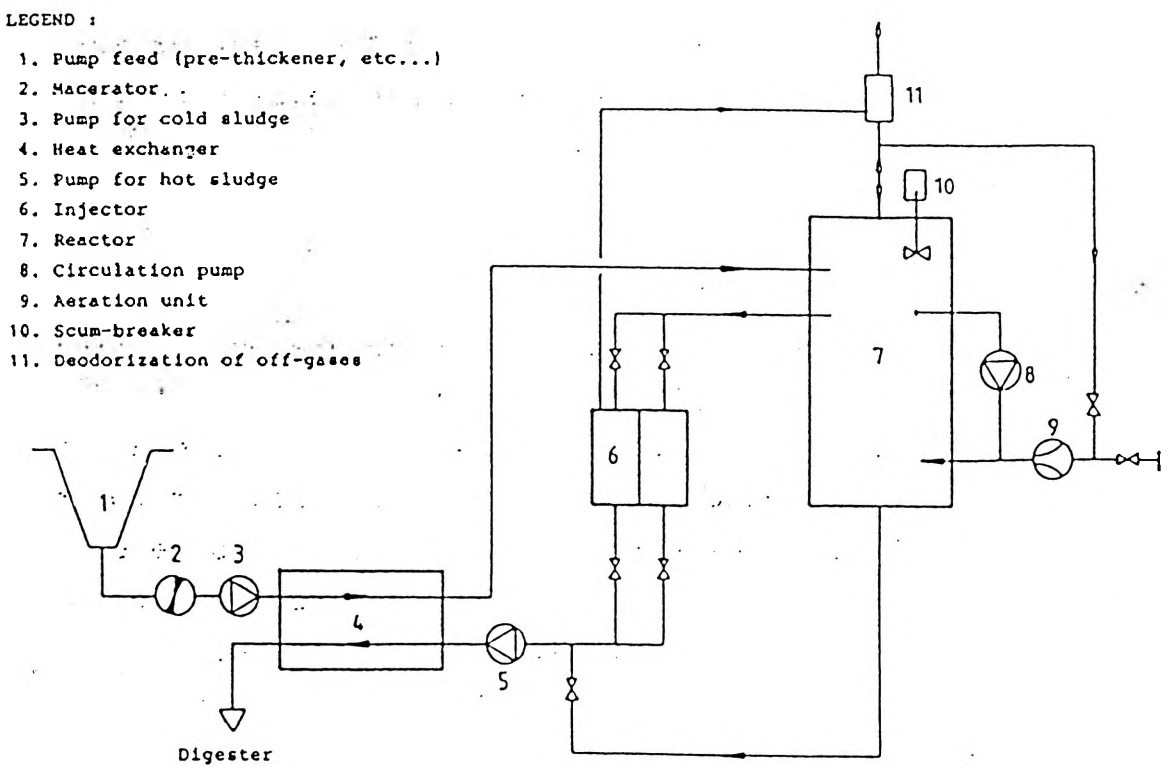


Figure 3.2 Schematic of a typical Anaerobic Thermphilic Process[19]

4. Theory and Analysis

4. Theory and Analysis

4.1 Microwave Theory

The majority of this Section on microwave theory has been sourced from references (16), (20) & (21).

4.1.1 History

Microwave techniques and many of the applications of microwaves were developed during and just prior to World War II when considerable work concentrated on the design and manafacture of microwave radar, navigation and communications equipment for military use. Much credit for this development belongs to the British Scientist, the most prominent responsible organisation being the Telecommunications Research Establishment at Malvern. Research was also pursued in the United States and Canada by the Bell Telephone Laboratories, General Electric, Sperry, Gyroscope Company and the Radiation Laboratory of the Massachusetts Institute of Technology.

Although most of the initial work was for military requirements, many peacetime uses of microwaves were developed just after World War II. One of these was microwave heating.

4.1.2 Characteristics of Microwaves

Microwaves cover a broad spectrum of frequencies, usually considered to range from 300MHz to 300GHz. The term microwave, however, denotes techniques and

concepts used as well as a range of frequencies. Microwaves may be transmitted through hollow metallic tubes and may be forced into beams by the use of high gain antennae.

Microwaves also change direction when traveling from one dielectric material to another, similar to the way light rays are refracted when they pass from air into water. Microwaves travel in the same manner as light waves. They are reflected by metallic objects, absorbed by some dielectric materials and transmitted without significant absorption through other dielectric material. For example, water, carbon and food with high water content are good microwave absorbers, while glass , ceramics and most thermoplastic materials allow microwaves to pass with little or no absorption.

Microwaves travel in free space at the speed of light. The free space wavelength, λ_o is related to frequency by the equation,

$$\lambda_o = \frac{c}{f} \qquad \text{...(4.1)}$$

where:

c = speed of light (3×10^{10}cm/s)

f = frequency of oscillations (2.45×10^{9}Hz)

λ_o = wavelength in free space (cm)

Hence for the microwave heating frequency used in Australia (2.45GHz), the free space wavelength is,

$$\lambda_o = \frac{3 \times 10^{10}}{2.45 \times 10^{9}}$$

$$= 12.24 \text{ cm}$$

4.1.3 Dielectric Heating

A dielectric material is defined by the real and imaginary components of the complex permittivity, ε^*,

$$\varepsilon^* = \varepsilon' - j\varepsilon^* \quad \text{(farads/meter)} \qquad ...(4.2)$$

When ε is normalised with respect to the dielectric permittivity of free space, ε_o

$$\varepsilon_o = \frac{10^{-9}}{36\pi} \quad \text{(farads/metre)} \qquad ...(4.3)$$

It gives the complex relative permittivity

$$\frac{\varepsilon}{\varepsilon_o} = k' - jk^* \qquad ...(4.4)$$

where k' is the relative permittivity or relative dielectric constant.

The loss tangent, tan δ, also called the dissipation factor, represents the energy loss characteristic of a material.

$$\tan\delta = \frac{k^*}{k'} \qquad ...(4.5)$$

where k^* is the relative loss factor also referred to as the loss factor and is the product of the dielectric constant and the loss tangent.

$$k^* = k' \tan\delta \qquad ...(4.6)$$

4.1.4 Microwave Heating Mechanisms

When microwaves are intercepted by dielectric materials such as water, they interact with the dielectric material giving up energy which results in a temperature increase of the material. There are two main mechanisms by which microwaves produce heat in a dielectric material. These are dipole rotation and ionic polarisation. However, dipole rotation is the most dominant heating mechanism in most water based materials. There are other mechanisms which prevail in unique situations, for instance, in the heating of ferromagnetic materials and with gases under reduced pressure. However these mechanisms will not be discussed in the present work.

4.1.4.1 Dipole Rotation

The dipole rotation heating mechanism shown in Figure 4.1, is dependent on the existence of polar molecules as found in water.

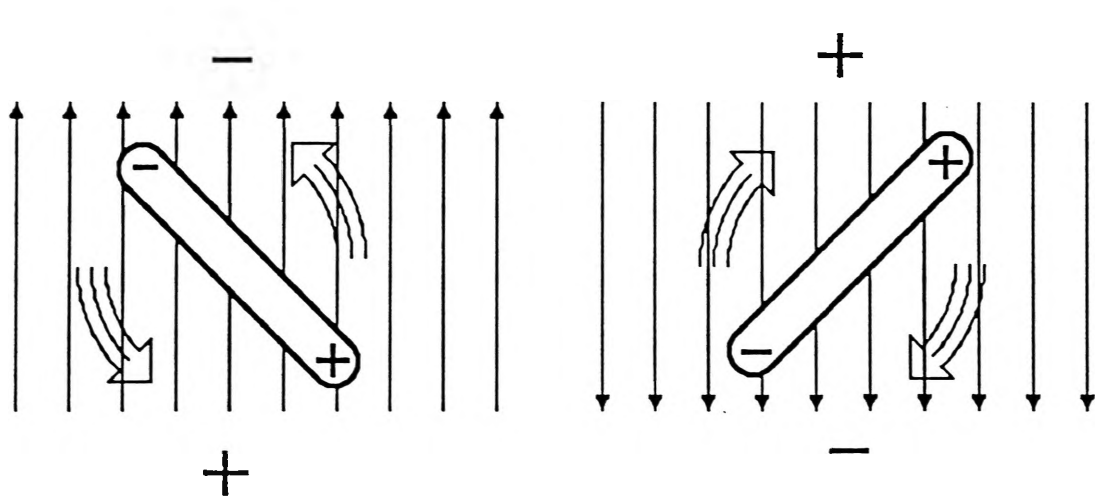


Figure 4.1 Dipole rotation due to a changing field.

Under normal conditions, polar molecules are randomly orientated. In the presence of an electric field, the polar molecules line up with the field. As an alternating field is applied, the polarity of the field is varied at the rate of the microwave frequency and the molecules attempt to align themselves with the changing field.

Heat is generated as a result of the rotation of the molecules. When the field is removed, the molecules return to their random orientation. The amount of time required to realign depends on the size of the molecule.

Microwave heating is also dependent on the physical state of the material. In ice, the movement of water molecules in a microwave field is restricted and therefore ice is a poor microwave absorber. As the temperature of a material increases, the molecules tend to line up more rapidly and return to the random state more rapidly.

4.1.4.2 Ionic Polarisation

Ionic polarisation occurs when ions in solution move in response to an electric field. Ions carry an electric charge and are accelerated by the electric field. Kinetic energy is given up by the field to the ions which collide with other ions, converting kinetic energy into heat. The more concentrated the solution, or the more dense the solution, the greater is the frequency of collisions resulting in more kinetic energy released.

4.1.5 Energy Conversion

An approximation of the amount of microwave energy converted to heat in a dielectric material is given by the equation,

$$P_D = 55.61\ E^2\ f\ k''\ \tan\delta \times 10^{-11} \quad \ldots(4.7)$$

where:

P_D = power dissipated (W/m^3)

E = electric field strength (V/m)

f = frequency (Hz)

k" = loss factor

$\tan\delta$ = loss tangent

Two of the above parameters, namely field strength E, and frequency f, are properties of the energy source. The parameters, relative dielectric constant and the loss tangent are properties of the material being heated. Increasing the value of any of these factors increases the amount of energy converted.

Selection of the highest available frequency and the highest possible field strength will maximise the energy conversion. It would appear the logical factor to increase would be the field strength, since it is a square function. However, in some materials and some microwave applicators field strength is limited by voltage breakdown considerations and chamber surface current characteristics.

4.1.6 Penetration Depth

Penetration depth is defined as the distance from the surface of a dielectric material at which the incident power drops to 1/e, ie to about 37%. The equation for the attenuation of the electric field is,

$$P = P_0 e^{-2\alpha d} \qquad ...(4.8)$$

where:

P_0 = incident power (W)

P = power at penetration depth (W)

α = attenuation constant

d = penetration depth (m)

e = 2.718282

If we let

$$\frac{P}{P_0} = e^{-1}$$

then,

$$e^{-1} = e^{-2\alpha d}$$

Taking the natural log of both sides of the equation,

$$-1 = -2\alpha d$$

hence,

$$d = \frac{1}{2\alpha} \qquad ...(4.9)$$

Penetration is also expressed as the half-power depth; the depth from the surface of a material at which the power has reduced to one-half of the incident power, ie,

$$\frac{P}{P_o} = \frac{1}{2}$$

then,

$$e^{-2\alpha d} = \frac{1}{2}$$

taking the natural log of both sides,

$$\ln e^{-2\alpha d} = \ln\left(\frac{1}{2}\right)$$

$$-2\alpha d = -0.693$$

Rearranging in terms of d,

$$d = \frac{1}{2.885\,\alpha} \qquad \text{...(4.10)}$$

The attenuation factor can be calculated by substituting known values for k' and tan δ into the equation,

$$\alpha = \frac{2\pi}{\lambda}\left[\frac{k'}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)\right]^{1/2} \qquad \text{...(4.11)}$$

The penetration depth for water at different temperatures is tabulated in Table 4.1.[21] This data is for water excited by a frequency of 3GHz and hence is approximately correct for the microwave heating frequency of 2.54GHz.

Table 4.1 Penetration depths for water at 3GHz

Temperature (^{O}C)	Penetration depth (cm)
1.5	1.1
1.8	1.8
25	2.3
35	2.9
45	3.6
55	4.4
65	5.2
75	6.2
85	7.7
95	9.4

4.2 Continuity Equation

The continuity equation is really a mathematical statement of the principle of conservation of mass. Consider a steady flow process through the control volume (shaded portion) of the stream tube depicted in Figure 4.2.

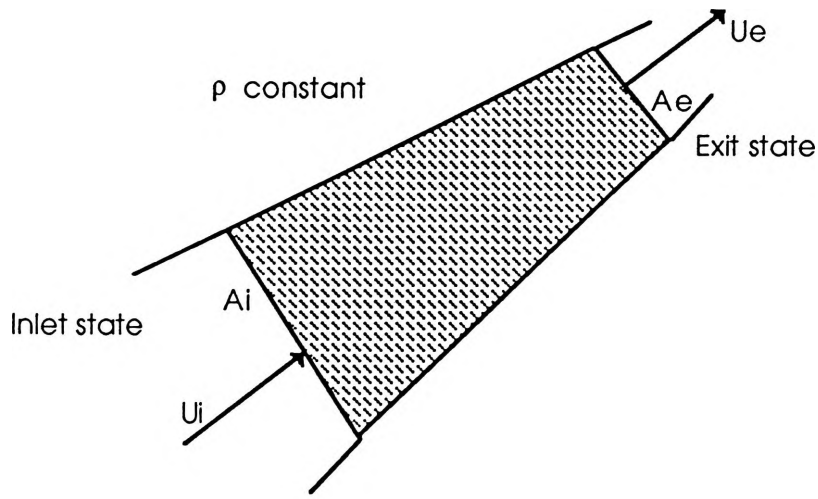


Figure 4.2 Steady flow through a stream tube

The mathematical derivation is outlined in many texts,[22] and is stated here as,

$$\dot{m} = \rho U_i A_i = \rho U_e A_e \qquad ...(4.12)$$

where:

$\dot{m}$ = mass flow rate (kg/s)

ρ = average density (kg/m^3)

U = average velocity (m/s)

A = cross-sectional area (m^2)

i,e = refer to the initial and exit states, respectively

For an incompressible process ρ is constant, it follows that,

$$Q = U_i A_i = U_e A_e \quad ...(4.13)$$

where:

Q = Volumetric flow rate (m^3/s)

4.3 First Law of Thermodynamics

The first law of thermodynamics is essentially the law of conservation of energy and can be stated as, " the energy going into a system, minus the energy going out of a system, equals the change in energy stored in the system." Its mathematical derivation is outlined in many texts[22] and for analysis of thermodynamic systems over a specific control volume, the equation can be expressed as,

$$\dot{Q}_{cv} + \dot{m}\left(h_i + \frac{U_i^2}{2} + gZ_i \right) = \dot{m}\left(h_e + \frac{U_e^2}{2} + gZ_e \right) + W_{cv} \quad ...(4.14)$$

where:

$\dot{Q}_{cv}$ = rate of heat transfer for the control volume (kW)

$\dot{m}$ = mass flow rate (kg/s)

h = enthalpy (kJ/kg)

U = velocity (m/s)

g = gravity (m/s^2)

Z = elevation (m)

W_{cv} = rate of work for the control volume (kW)

i,e = refer to initial and exit states, respectively

However, applying this equation on an ideal, steady-state, steady-flow process system designed for processing water, many terms are negligible and approach zero. For such a process equation 4.13 can be simplifed to,

$$\dot{Q}_{cv} + \dot{m}\, h_i = \dot{m}\, h_e$$

$$\dot{Q}_{cv} = \dot{m}\,(h_e - h_i) \qquad \text{...(4.15)}$$

For a process involving water, the entropy of the inlet and exit states can be determined from steam tables. However, considering the ideal process is at constant pressure, equation 4.14 can be simplified by using the constant pressure specific heat relation,

$$C_p = \left(\frac{dh}{dT}\right)_p \qquad \text{...(4.16)}$$

Intergrating,

$$\Delta h = C_p\, \Delta T$$

$$h_e - h_i = C_p\,(T_e - T_i)$$

Where Cp is the specific heat pressure constant for water (4.184 kJ/kg ^{o}C)

Therefore,

$$\dot{Q}_{cv} = \dot{m}\, C_p\,(T_e - T_i) \qquad \text{...(4.17)}$$

4.4 Efficiency and Effectiveness

The efficiency η of a process involving water can be expressed as the ratio of output energy to the applied energy or simply,

$$\eta = \frac{\dot{Q}_{cv}}{\text{Input Power}} \qquad \text{...(4.18)}$$

However when considering sewage sludge, which is a mixture of water and solids the specific heat constant is unknown. To offset this deficiency the specific heat constant of sludge will be assumed to be that for water. Justification for this assumption is based on the fact that sludge is typically 80% water. In view of this assumption the term 'efficiency' is not entirely correct and shall be redefined as effectiveness.

Therefore, the effectiveness η_s of a process involving sewage sludge is defined as,

$$\eta_s = \frac{\dot{Q}_{cv}}{\text{Input Power}} \qquad ...(4.18a)$$

4.5 Fluid Resistance

Losses occur in pipelines because of resistances created by bends, elbows, joints, jackets, surface roughness of pipes, etc. These are called head losses and for turbulent flow the mathematical equation[23] to model these losses is expressed as,

$$h_f = \frac{K\ U^2}{2g} \qquad ...(4.19)$$

where:

h_f = head loss (m)

K = loss coefficient (dimensionless)

U = velocity (m/s)

g = gravity ($9.8 m/s^2$)

Turbulent flow is considered to occur at Reynolds numbers in excess of 2000 to 4000. Reynolds number is given by the equation,

$$R_e = \frac{U\ D\ \rho}{\mu} \qquad ...(4.20)$$

where:

R_e = Reynolds number (dimensionless)

U = velocity (m/s)

D = pipe diameter (m)

ρ = density of fluid (kg/m3)

μ = absolute viscosity (Pa.s)

5. Design of Plant

5. Design of Plant

5.1 Introduction

Following the successful results of the initial research, the initial prototype required further work to improve the design. The aim was to design and build a continuous operating prototype, to enable microwave treatment of sewage sludge up to a level of complete sterilisation. The basic design parameters of the unit were as follows.

- Maximum operating temperature = 130°C,
- Maximum operating pressure = 600kPa,
- Maximum flow rate (ΔT=60°C & P = 40kW & η = 80%, eqn 4.18) = 457kg/hr,
- Minimum flow rate (ΔT=120°C & P = 20kW & η= 80%, eqn 4.18) = 114kg/hr.

Testing was conducted at the Shellharbour Sewage Treatment Plant. After successful commissioning of the plant, trials were undertaken to determine optimum operating parameters for levels of treatment ranging from pasteurisation to sterilisation. A brief summary of the plant design is outlined below and then expanded in detail later.

The initial microwave pressure treatment plant described in Section 2.4 was effective but cumbersome. The pressure vessel could only hold a limited amount of sludge before it required emptying. The pyrex glass pipe suspended inside the microwave oven cavity was vulnerable to breakage and its operation governed by the safe pressure limit imposed at high temperatures.

The first improvement to the design of the system was to apply microwave energy to the sludge using a stainless steel microwave pipe-heater. In this method of microwave heating, the cavity was essentially a stainless steel pipe with a microwave transparent plastic liner fitted inside the "pipe-cavity" to contain the sludge for heating.

The next design refinement was to simplify the mechanics of continuous pressure treatment of the sludge. The aim was to design a system to maintain a continuous pressure and able to release the hot sludge without depressurising the system. The hot sludge could have all three phases present, solid, liquid and gaseous at any one time. This was achieved by using a pair of peristaltic pumps in tandem (one to feed and one to discharge), driven by the same motor on a common shaft with a speed control to allow the delivery rate to be varied. This was a major design improvement and greatly simplified the mechanical operation of the processing plant.

A heat pipe installed between the feed and discharge peristaltic pumps enabled heat to be transferred from the hot sludge to the cold untreated sludge. The heat pipe was also an effective temperature limiter for the discharge pump liner which could otherwise have been destroyed due to excessive temperature. The cooling circuit for the magnetron water was also upgraded by the addition of an appropriate water pump and evaporative cooling tower.

5.2 Microwave Pipe Heater Technology

There were two technologies available for evaluation when designing an appropriate sludge processing plant. The first was the pyrex (or ceramic) pipe through a microwave cavity and the second was a "pipe heater" designed cavity.

The pyrex pipe through a microwave cavity was as used for the initial treatment plant. It had the advantages of being inexpensive and easily adapted to the existing cavity. However, it also had the serious disadvantages of being very delicate and vulnerable to breakage, especially at elevated pressures and temperatures and was also susceptible to thermal shock.

The pipe heater technology was also available for use. This was a specially manufactured microwave cavity incorporating a slanted wave guide entry into a 100 mm stainless steel pipe with a microwave transparent teflon liner to contain the material heated (Figure 5.1 & Photo 5.1). The pipe heaters temperature and pressure limitation corresponded to that which the teflon liner could safely contain. This design was certainly more industrially robust and shock proof than the pyrex glass pipe inside the microwave cavity arrangement. It did have disadvantages of being more costly to manufacture and was limited by the yield strength of teflon which varied with temperature.

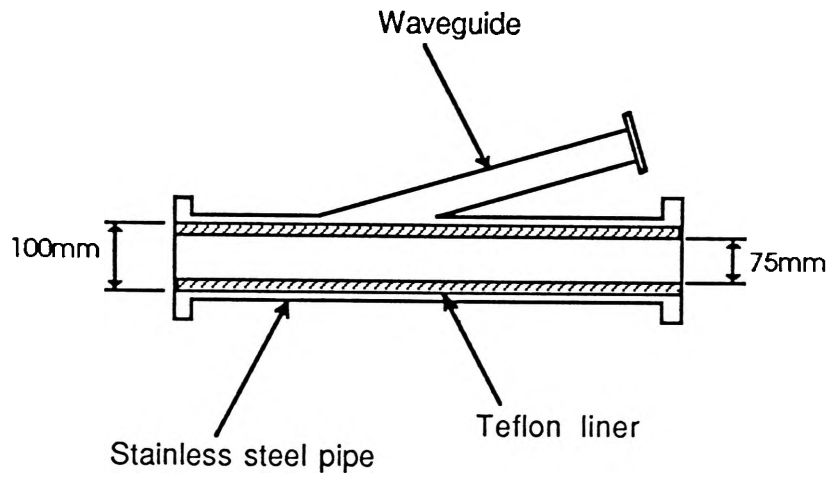


Figure 5.1 Schematic of "pipe heater"

A comparison of the two systems had been evaluated earlier by determining the efficiency of a 40kW microwave unit with a pyrex pipe through the cavity and a 15kW microwave unit incorporating pipe heaters.[24] Test results were conducted on tap water with the 40kW unit tested in two configurations; the pyrex pipe uninsulated and with insulation. The 15kW unit was tested in one configuration with no insulation on the outside of the stainless steel pipes. However, the teflon liners did provide a good degree of insulation but the inlet and exit tubes of the system were prone to heat loss. The average observed microwave efficiencies are summarised in Table 5.1.

Table 5.1 Average efficiencies for the 15 and 40kW microwave units

Microwave Unit	Average Microwave Efficiency
40kW unit without insulation	65.1%
40kW unit with insulation	81.5%
15kW unit	77.8%

The results of the 40kW unit with insulation and the 15kW unit are very similar. Considering these two configurations and the fact that the 15kW unit had margin for improvement by incorporating insulation, it was evident that the projected average efficiencies of both units would be similar. Hence, in the evaluation of the most appropriate technology for heating of the sludge, both systems should produce identical efficiencies, and the extra cost of the pipe heater was definitely warranted because of its industrial robustness.

5.2.1 Construction and Installation of Pipe Heater

The 40kW unit was originally designed as a portable conveyor belt drier.[25] It incorporated a 2.36 x 0.75m microwave cavity with a conveyor belt passing through longitudinally. Microwave power was supplied by eight 5kW magnetrons which were water and air cooled.

To enable the pipe heater to be fitted, the cavity and conveyor belt were removed. A support frame was made to appropriately locate the pipe heater so as to enable the electrical wires to reach each magnetron, negating the need for extension wires. The water and air cooling pipes had to be relocated because originally they were supported off the original microwave cavity.

Eight pipe heater sections were supplied by IMA, each section made to accommodate one magnetron. Two lengths of four sections were connected together by a 180 degree bend so the assembled pipe heater could sit in an similar position to the previous microwave cavity (Figure 5.2 & Photo 5.2).

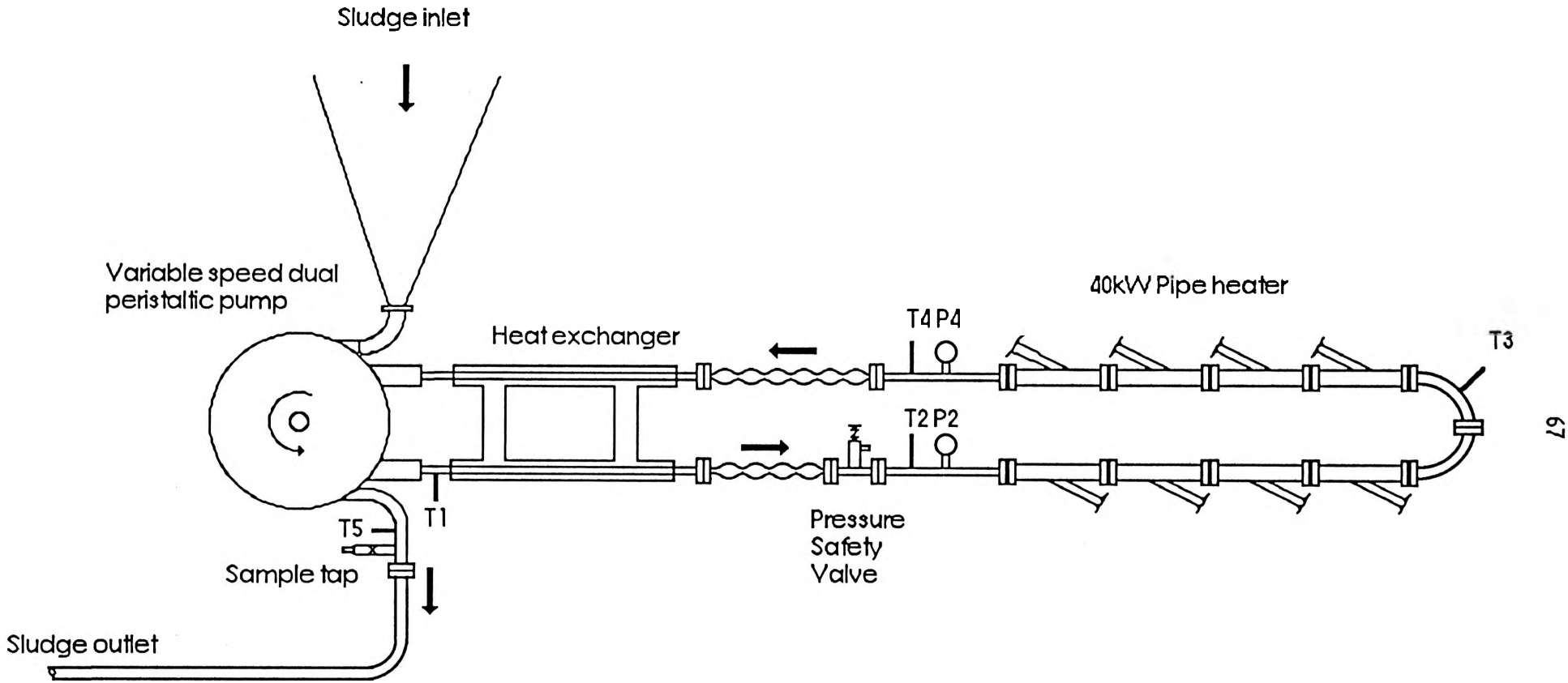


Figure 5.2 Schematic of system used for commissioning and first test run

Extension pipes were connected to the pipe heater ends so appropriate instrumentation could be connected. On the end of these extension pipes, sight glasses were installed so as to enable a visual inspection of the sludge flow. The pipe size was reduced from 75mm to 50mm by reducers to connect to the pressure treatment process and heat exchanger, described later. A safety pressure relief valve was also included in the system to safeguard against excessive pressure build up (Photo 5.3).

5.2.2 Mechanical Limits of Teflon Liner

Considering the teflon liner as a long thick walled cylinder, the exerted pressure on the cylinder is inside, whereas, the pressure outside the cylinder is zero. Hence, the pressure required to plastically deform the teflon liners can be calculated by the following equation,[26]

$$p_{yp} = \frac{\sigma_{yp} (r_o^2 - r_i^2)}{2r_o^2} \qquad ...(5.1)$$

where:

p_{yp} = pressure at the yield point (MPa)

σ_{yp} = yield strength (MPa)

r_o = outside radius (mm)

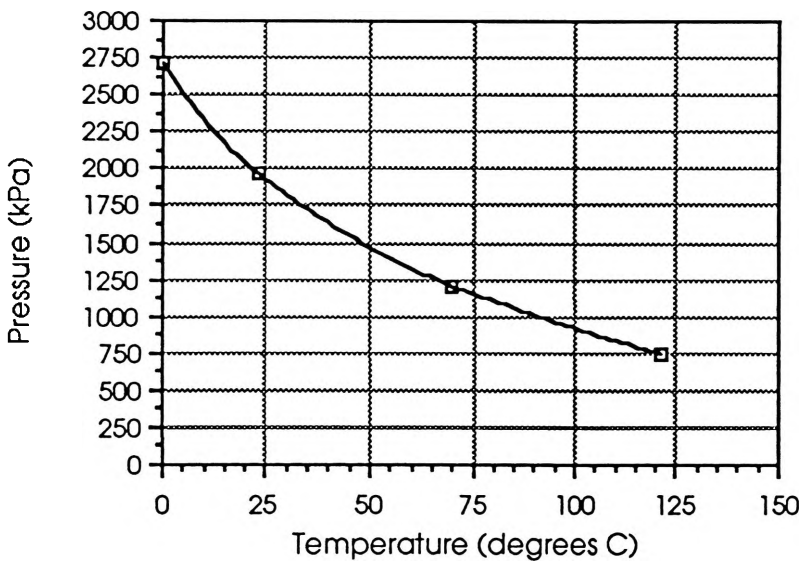
r_i = inside radius (mm)

The yield strength for the type of teflon used for the liners, with respect to various temperatures is shown in Table 5.2.[27] The corresponding yield pressure has also been calculated.

Table 5.2 Mechanical limits of teflon liner

Temperature (°C)	Yield strength (MPa)	Pressure (kPa)
0	12.40	2713
23	8.96	1970
70	5.51	1210
121	3.44	750

Figure 5.3 Graph of yield pressure for teflon liner



5.3 Continuous Pressure Treatment

Experience with the initial microwave treatment plant identified areas of the plant that needed improvements. The pumping of the sludge into the system was not a problem and could be achieved by positive displacement type pumps. The pressure vessel was also effective in maintaining the sludge at pressure. However it had its disadvantages.

The vessel did not have an automated valve to release the hot sludge and relied on an external compressor to initially maintain the system pressure. Start up procedure was difficult because it was necessary to ensure the initial sludge passing through the system was up to temperature and sterilised, so that the following treated sludge did not get reinfected as it passed through the vessel. Any device, such as a pressure vessel down stream of the heat treatment would also be prone to recontamination. Overall, it was cumbersome, bulky, costly and there was definitely a better solution.

The problem was to release the hot sludge, a mixture of solid and very fibrous matter, liquid effluent including the possibility of gaseous pockets to atmosphere, while maintaining a steady system pressure. The answer was to use a positive displacement pump to discharge the sludge from the system as well as pumping it into the system. The two pump answer had not been utilised elsewhere and was a new concept. However, it would prove very effective.

The positive displacement pump chosen for this task was a peristaltic pump. It was supplied by Westend Industries Pty Ltd and was selected because of the following advantages;

- Its ability to "run dry" without harm to the pump,
- The second pump was self cleaned by the heated sludge,
- Pump liner was temperature rated to 130°C,
- Geometry made it ideally suited for modification,
- Compactness,
- Cost effectiveness.

The type of peristaltic pump chosen used a 50mm bore and had been extensively used in the concrete industry and for other sludge applications. A 75mm bore would have been most desirable to enable the pipe system to be free from contractions but this size was not available. The 50mm pump's capacity was also well in excess of the theoretical maximum microwave pipe heater capacity. Hence, it was the most suitable pump size.

To perform the task required, a "dual peristaltic pump" was constructed using the components of two single pumps but incorporating one common body and centre shaft, (Figure 5.4 & Photo 5.4). It was driven by a 0.75kW electric three phase motor through a 140:1 reduction gearbox, selected to suit the theoretical flow rates for the pipe heater. The speed of the pump was controlled using an inverter on the electric motor. The inverter gave a digital readout of the operating frequency of the motor which enabled precise control and repeatability for pump speed settings.

There was a concern whether the second pump would pump at a marginally greater capacity due to the forced feeding of the sludge into it. If this did occur the second pumps liner could be reduced in length marginally and therefore reduce the volumetric capacity marginally and compensate for its increased pumping rate. The sight glasses were used to visually investigate this possibility. However this did not seem to be a problem. The sight glasses were hence removed because of vulnerability to breakage.

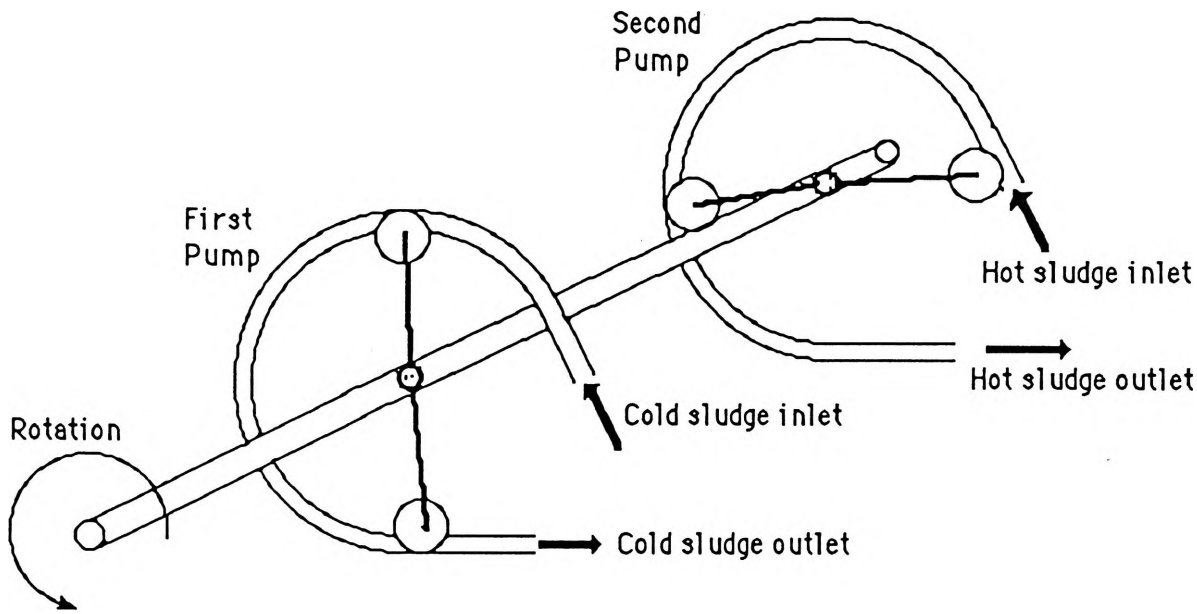


Figure 5.4 Schematic of "dual peristaltic pump"

The dual peristaltic pump was a major improvement and proved to be a very simple and elegant solution to discharging the hot sludge. It greatly simplified the mechanical operation of the plant.

5.4 Heat Exchanger

It was desirable to place a heat exchanger across the inlet and outlet to the dual peristaltic pump to not only recover some energy but also help preserve the liner of the second pump. The type of heat exchanger used was a very simple, compact and elegant device called a heat pipe. The configuration of the device is shown in Figure 5.5.

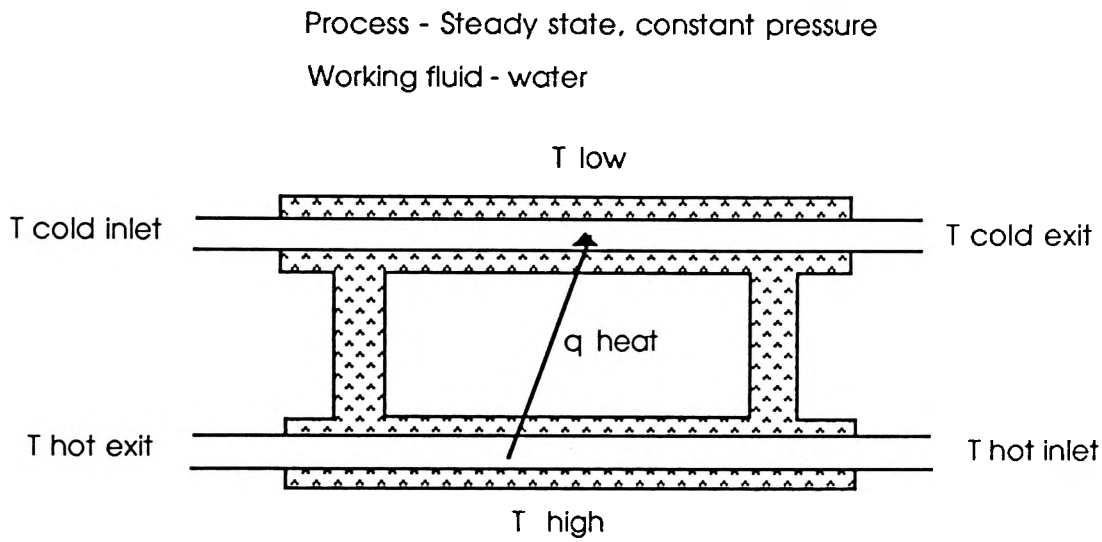


Figure 5.5 Schematic of heat exchanger

The cold and the hot sludge pipes were made of copper to enable efficient heat transfer. Encapsulating these pipes was another system of pipes as shown by the shaded part of Figure 5.5. A condensible fluid, in this case water, filled the shaded piping system. When heat was added to the high temperature side (T high) the working fluid was vapourised and would rise to the low temperature side (T low) of the heat exchanger. The cold side extracted the heat from the vapourised working fluid which condensed and returned to the hot side of the heat exchanger. This mechanism transferred heat from the hot exit sludge pipe to the cold inlet sludge pipe.

This heat exchanger only really started working when the hot sludge was heated above 100°C causing the working fluid to vapourise. Below 100°C the heat exchanger worked primarily as a heater. It proved to be a very effective unit and worked best when the hot sludge temperature exceeded 110°C.

5.5 Cooling Water

The cooling water design of the original 40kW microwave drier was inadequate and needed improving. The problem was, basically insufficient cooling capacity in the plant to liberate the waste heat generated by the magnetrons. The water pump was a borrowed unit which served as a stop gap for a replacement unit. The cooling water pipes were removed because they were connected to the old microwave cavity. Overall, the entire cooling water circuit required redesign and improvement.

The cooling water was needed to cool the YJ1600 Philips magnetrons used in this unit. Specifications require a minimum flow of 2 litres/minute per magnetron. However from experience, this flow rate is too low and should be typically at least 6 litres/minute for multi-magnetron cooling networks. Furthermore the maximum cooling water temperature should not exceed 65°C, (Appendix A).

In designing an appropriate cooling water circuit, it was first necessary to determine the loss coefficient for the YJ1600 magnetron. An experimental test rig was designed to evaluate this and is outlined in Appendix B. The result is quoted here,

YJ1600 cooling water loss coefficient $K = 96$

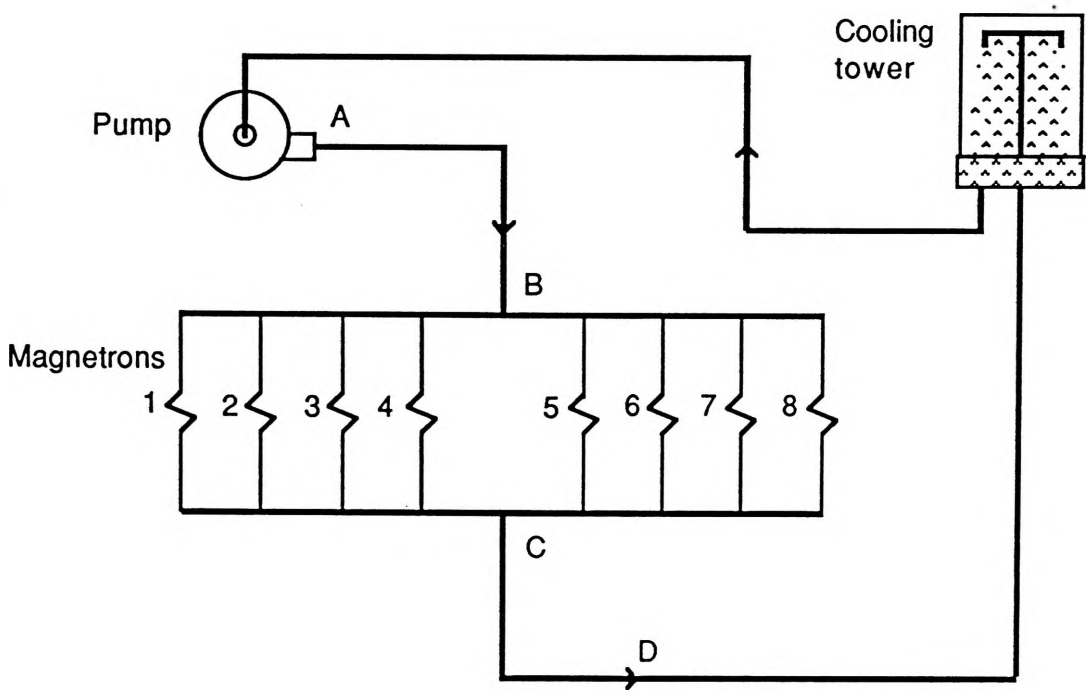


Figure 5.6 Schematic of cooling water circuit

Neglect pipe line losses at this stage because head loss through the magnetron is much greater than the head loss for the rest of the pipe system. Using equation 4.19

$$h_f = \frac{K\ U^2}{2g} \qquad \text{...(4.19)}$$

and considering,

$$Q_T = Q_1 + Q_2 + ... + Q_8$$

where, 1,2,....8 refer to each magnetron.

However,

$$Q_1 = Q_2 = \ldots\ldots = Q_8 = \frac{Q_T}{8}$$

where, Q_T is the total volumetric flow.

Therefore, from equation 4.13,

$$Q_T = 8UA$$

Rearranging,

$$U_n = \frac{Q_T}{8A}$$

where: n = 1,2,....8 refering to each magnetron,

Substituting into equation 4.19 and assuming 10% of magnetron losses to be losses in the rest of pipe system,

$$h_f = \frac{1.1\ K\ (\frac{Q_T}{8A})^2}{2g} \qquad \text{where,} \quad A = \frac{\Pi}{4} 0.0125^2\ m^2$$

$$g = 9.81\ m/s$$

$$h_f = 5.55 \times 10^6\ Q_T^2 \qquad \ldots(5.2)$$

Substituting various values for Q_T into equation 5.2 yields the values shown in Table 5.3.

Table 5.3 Head loss for various values of flow rate

Flow rate (L/s)	Head loss (m)
0	0
0.5	1.38
1.0	5.55
1.5	12.48
2.0	22.20

Referring to the performance chart for a proposed pump, the head loss versus flow rate for the system can be plotted and the intersection point with the performance curve is the theoretical flow of the system using that pump. Choosing a Grundfos CH4 pump, the expected flow for the corresponding pumps are, (Appendix C),

Table 5.4 Theoretical flow for cooling circuit

Type of pump	Flow for system	Flow for each magnetron
CH4-20	1.40L/s	10.5L/min
Ch4-30	1.60L/s	12.0L/min
Ch4-40	1.80L/s	13.5L/min

From Table 5.4, any of the pumps listed were suitable. Therefore, selecting the CH4-20 to provide a theoretical 10.5L/min. The flow can be throttled back if excessive. However this was not necessary. Testing of the system after the selected pump was installed (without a cooling tower) indicated an actual flow rate for the system of 72L/min, or 9L/min per magnetron. Selection of suitable cooling tower was possible now based on the actual flow.

Referring to the Coolboy cooling tower selection chart (Appendix D), and considering the worst possible ambient conditions,

- Nominal flow = 1.2L/s
- Maximum expected power dissipation required, (based on an efficiency of 72% for 8 magnetrons)

$$P = \frac{40kW}{0.72} - 40kW$$

$$= 15.6kW$$

- This corresponds to a temperature rise of 2.7°C, (eqn 4.17 for a flow rate of 1.15L/sec),
- Maximum design cooling water temperature, say 35°C,
- Now, range of temperature is 3.1°C, hence the water outlet temperature is 31.9°C,
- Selecting an ambient wet bulb temperature of 25°C, therefore approach temperature is, 31.9 - 25 = 6.9°C.

Using the manafacturer's selection chart, the appropriate cooling tower is well below the rated capacity of type CB-5. However, the maximum water flow specified for the CB-5 is 0.88L/sec. Selecting the next larger size cooling tower (CB-8) has a more appropriate maximum cooling flow of 1.46L/sec. Therefore this was the most suited cooling tower unit. Testing with this cooling tower showed ample cooling capacity for the magnetron cooling water, as expected.

5.6 Instrumentation

Instrumentation of the process was essential for the following reasons,

- greater knowledge of process,
- repeatability,
- performance monitoring,
- improvement and optimisation,
- scale up and economic examination.

An examination of the process revealed that there were four main groups to which instrumentation was required. These were:

- electrical power,
- microwave power,
- sludge temperature and pressure,
- sludge flow rate.

Each group is discussed in the following sections with most instrumentation shown in Photo 5.5.

5.6.1 Electrical Power

The electrical power into the microwave unit is a useful quantity when determining the total energy consumption of the plant for possible economic evaluation. It was measured by a Microvia MK 11 Energy Analyser by Elcontrol, an unit which can display or printout up to twelve electrical measurements.

5.6.2 Microwave Power

The microwave power developed by each magnetron can be varied individually from approximately 0.5 to 5kW. The magnetrons are 72% efficient in transferring electrical power to microwave power (Appendix A).

A schematic of the microwave circuit used to power each magnetron is shown in Figure 5.7. A simplified explanation of how the microwave energy is controlled is as follows. For further explanation of the circuitry, refer to the technical publication.[28]

Figure 5.7 Schematic of standard power supply for Philips magnetron YJ1600[28]

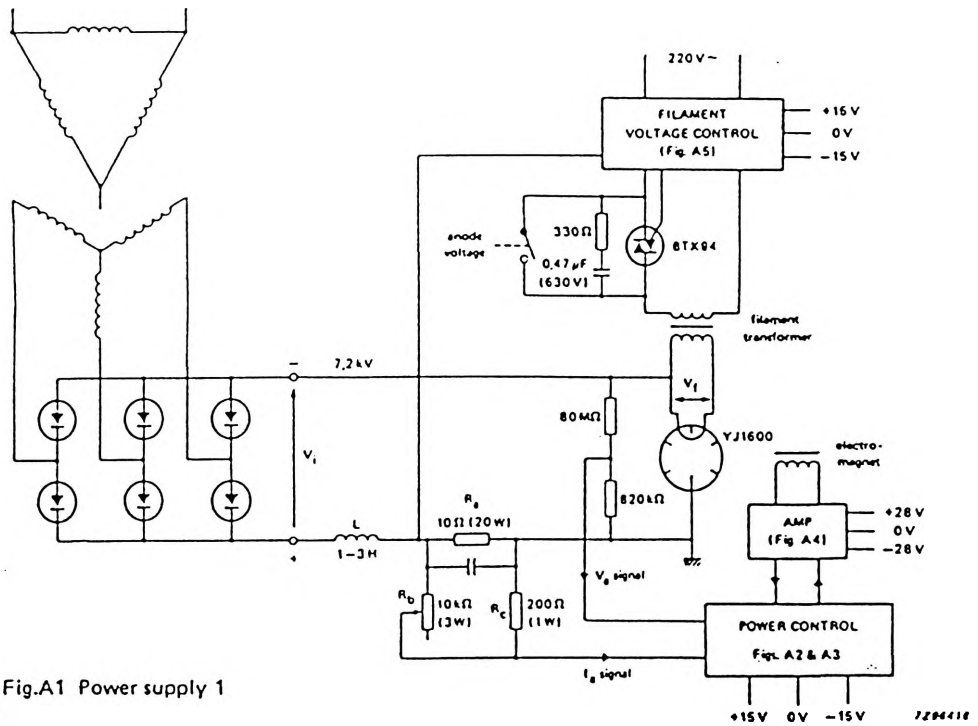


Fig.A1 Power supply 1

For each operation of the magnetrons, there is a 15 second delay in which the filament transformer applies V_f to the filament anode of the magnetron. This warms the filaments inside the magnetron to temperature in the vicinity of 2000°C. After 15 seconds warm up, a high voltage V_I is applied across the magnetron filaments and earth, which enables an electromagnetic voltage to be produced at the antenna of the magnetron. The power output is proportional to the current I_A supplying the electromagnetic coils of the magnetron. This current I_A can be adjusted by a variable resistor potentiometer. There is a variable resistor potentiometer and a digital voltmeter for each magnetron so the electromagnetic coil current can be monitored.

The current I_A is variable from approximately 50mA at idle to 950mA at full power. The power output of each magnetron can be calculated using the equation,

$$P_{mic} = \eta V_I I_A \qquad ...(5.3)$$

where:

P_{mic} = microwave power (kW)

η = efficiency of magnetron (72%)

V_I = high voltage to magnetron (7.200kV)

I_A = electromagnetic coil current (0.050 to 0.950A)

5.6.3 Sludge Temperature and Pressure

The sludge temperature was measured by K-type thermocouples placed in various positions along the system (Figure 5.2). These readings were relayed to a digital thermometer via a switching box. This meant that only one temperature reading could be viewed at any one time, which was quite sufficient for this process. It proved to be an economical but efficient system. Cooling magnetron water was also monitored through the switching box.

Two 0 to 600kPa pressure gauges were placed in the system; one to monitor the pressure on the inlet side of the pipe heater and one on the exit side. Pressure gauges were oil filled and chosen with large diaphram seals to overcome possible errors due to sludge temperature. Diaphram seals were welded as close as possible to the inner surface of the pipe so as to prevent any dead spots where sludge could accumulate and/or cause false readings or reinfection.

5.6.4 Sludge Flow Rate

The sludge flow rate was measured experimentally by measuring the time required to fill a certain mass in a bucket. It was uneconomic to continuously measure the flow rate using sophisticated flow rate monitors and there would have been concern as whether any device would accurately work on such viscous sludges.

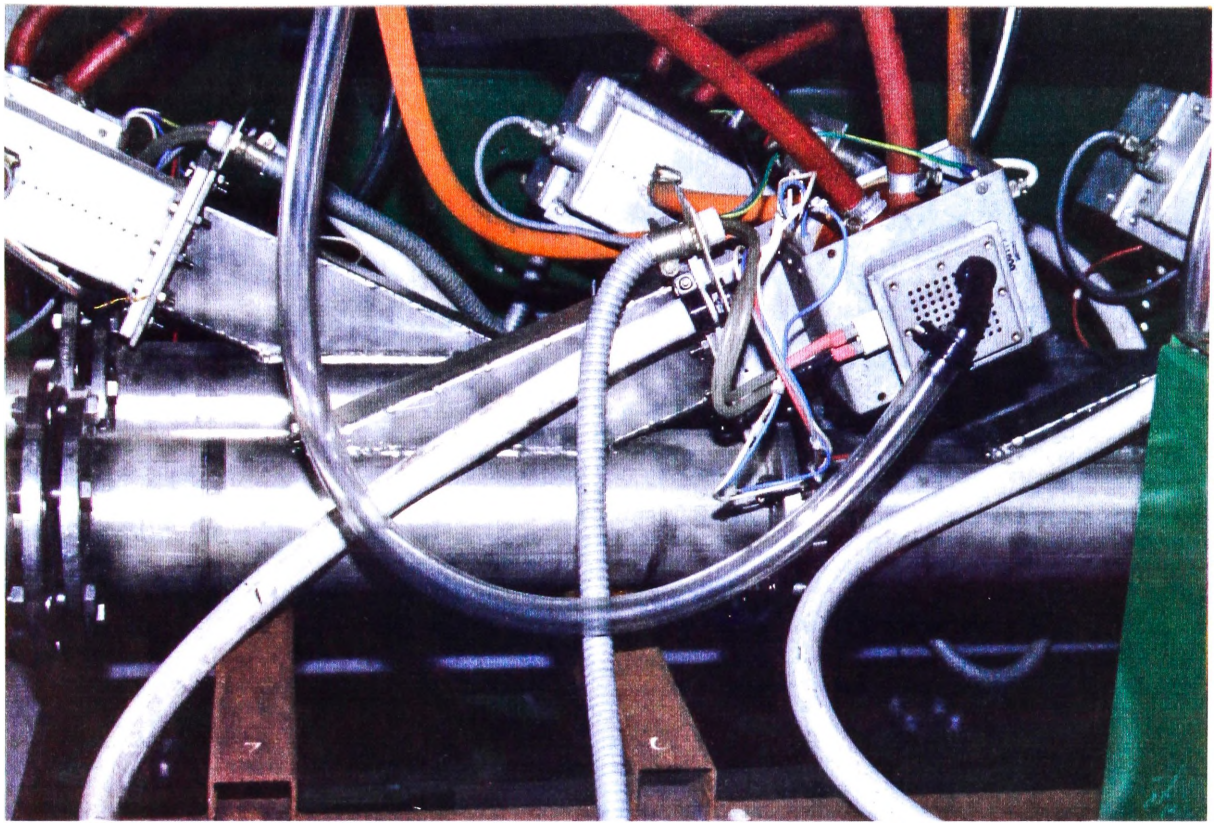


Photo 5.1 One pipe heater section is shown in the foreground incorporating a 5kW Philips YJ1600 magnetron.

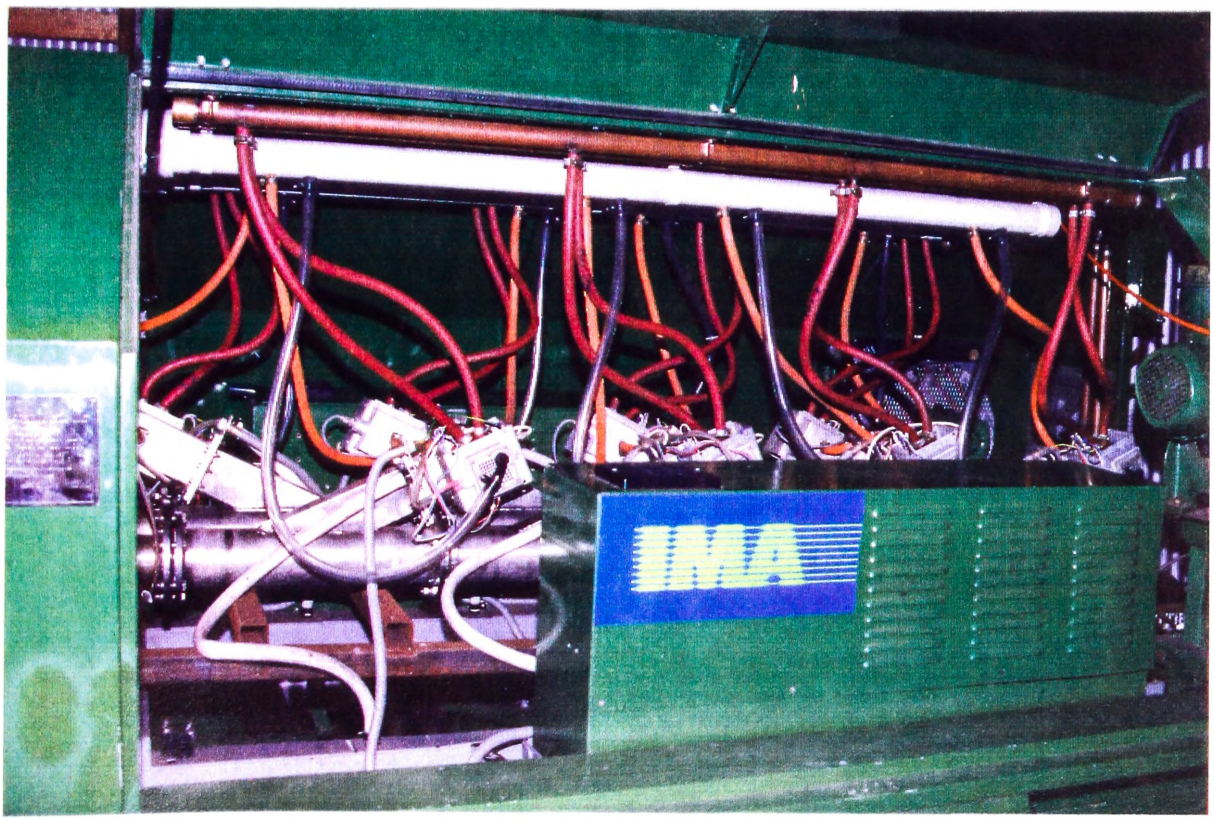


Photo 5.2 Eight pipe heater sections showing electrical wiring and plumbing.

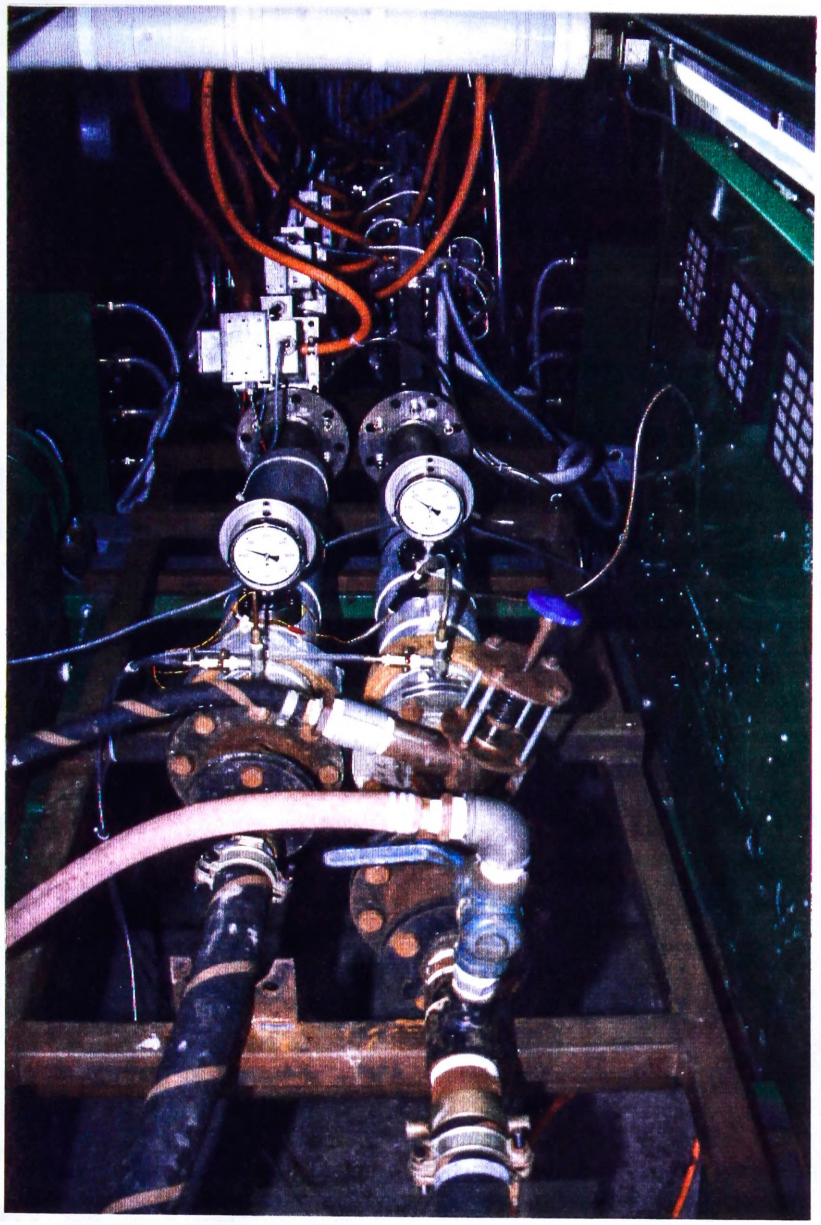


Photo 5.3 The 40kW pipe heater showing instrumentation and pressure relief valve in the foreground and pipe heater sections with attached magnetrons in the background.

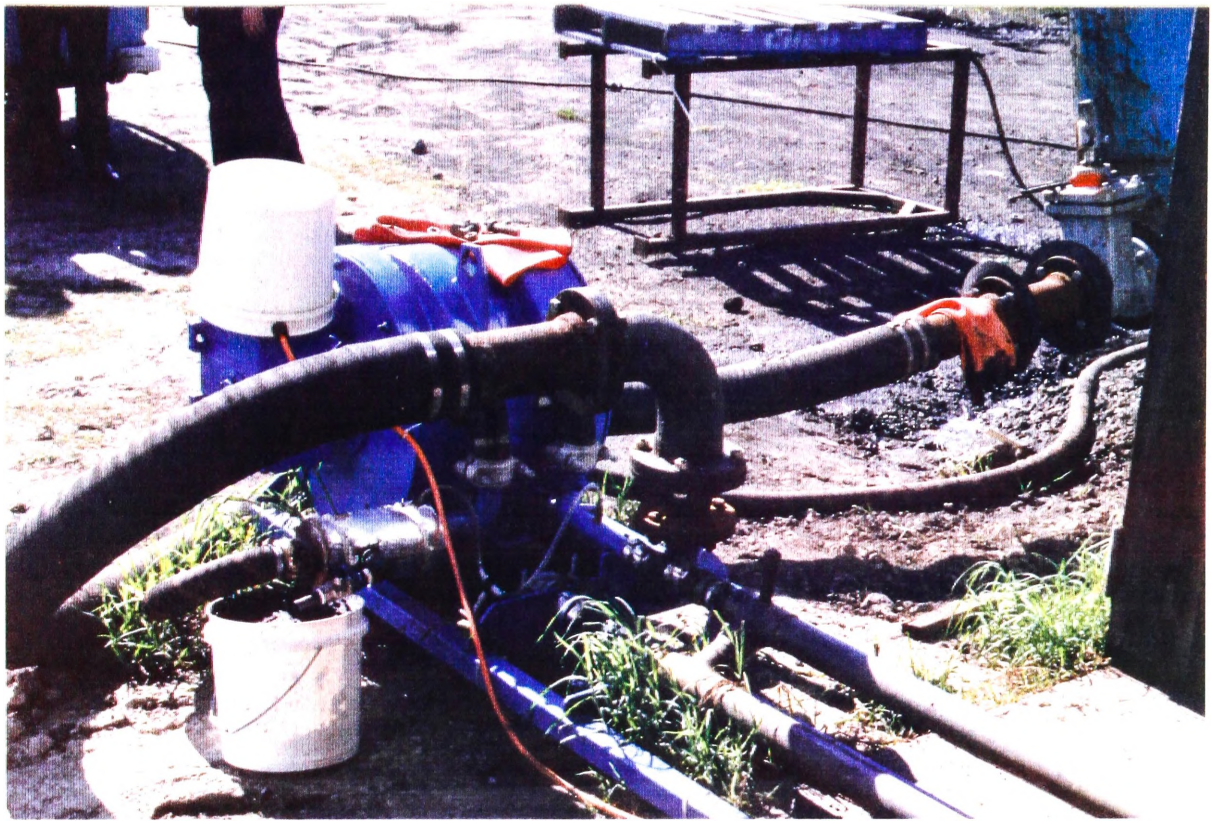


Photo 5.4 The dual peristaltic pump and attached heat exchanger.

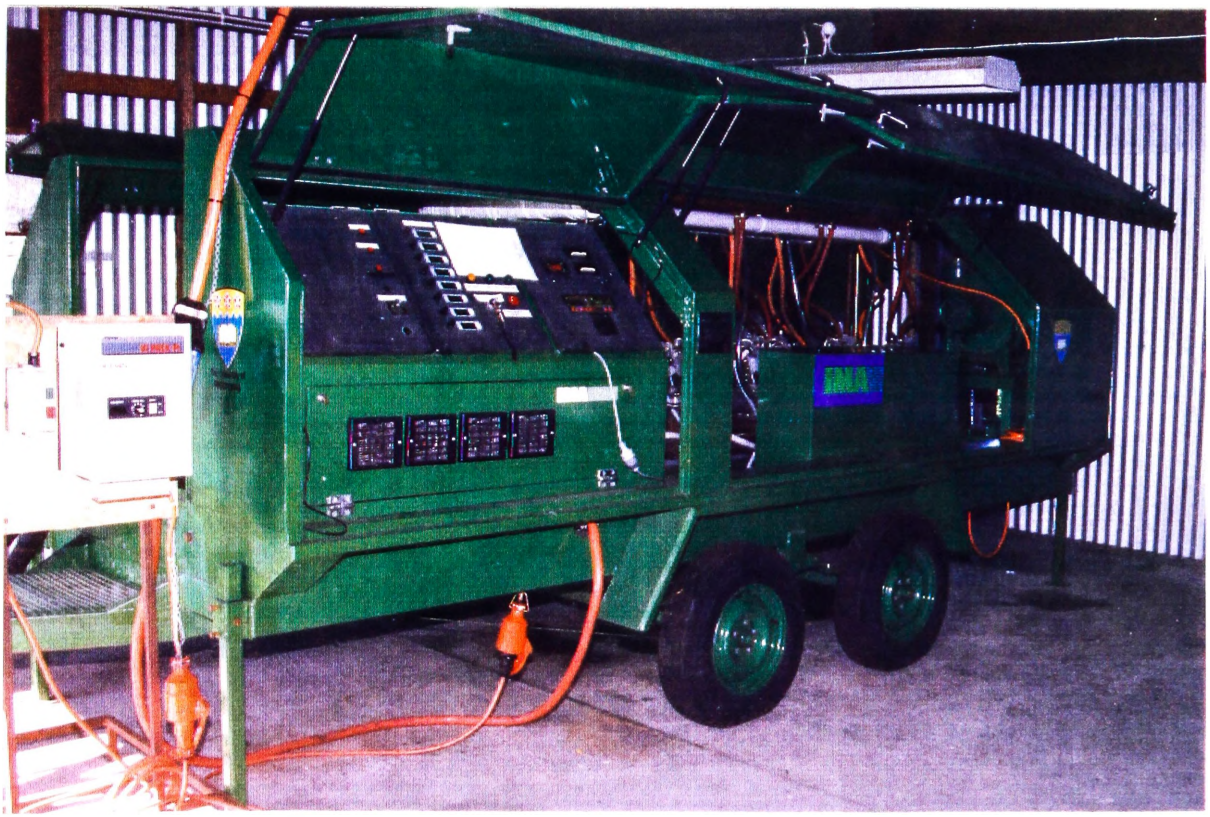


Photo 5.5 The 40kW microwave plant showing the control panel and variable speed drive.

6. Experimentation

6. Experimentation

6.1 Heating Rates for Sludge in Comparison to Water

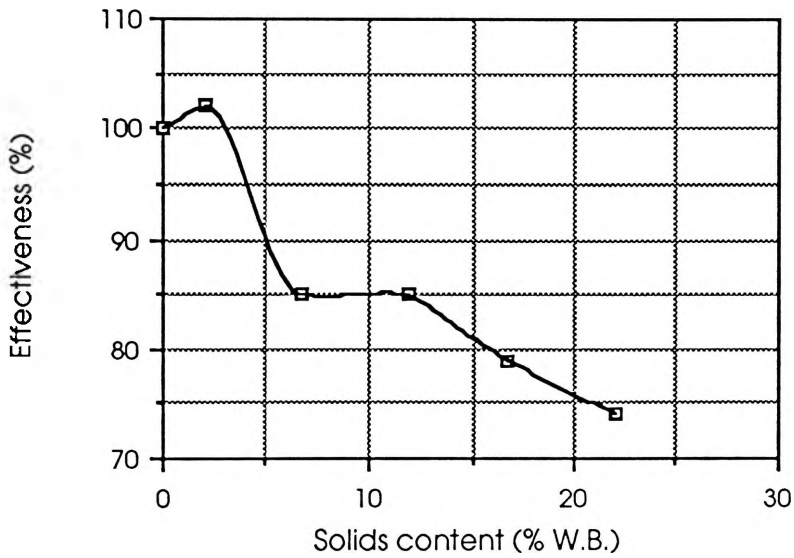
The aim of this experiment was to investigate the heat transfer to samples of varying sludge solids content in comparison to water. Solids contents of up to 22.1% were investigated. One kilogram samples were heated for 3 minutes in a modified Sharp 1300 Watt microwave oven and temperatures were recorded before and after heating. Results are shown in Table 6.1 and plotted in Figure 6.1. Equation 4.17 was used to determine the heat in the samples based on the specific heat of water. The effectiveness of heat transfer to the sludge was also determined (equation 4.18a).

Table 6.1 Heating rates of water and sewage sludge

Sample (W.B.%)	Initial Temp.(°C)	Final Temp.(°C)	Change in Temp.(°C)	Heat Tran.(kW)	Effectiveness (%)
Tap water	23.7	85.7	62.0	1.44	100
2.0%	23.5	86.5	63.0	1.47	102
6.7%	23.5	77.0	53.5	1.23	85
11.9%	23.5	77.0	53.5	1.23	85
16.7%	22.4	71 (E.84 C.58)*	48.6	1.13	79
22.1%	22.0	68 (E.88 C.48)*	46	1.07	74

* "E." refers to average edge temperature and "C." refers to average centre temperature of the sample. The average of these two temperatures was calculated to estimate the sample bulk temperature.

Figure 6.1 Effectiveness of heat transfer in comparison to water versus sludge solids content



6.2 Tests using Water

The unit was trialled at MARC's Coniston Laboratory, on tap water to check its performance with particular attention paid to the dual peristaltic pumping rate and the systems performance at temperatures in excess of 100°C. Figure 5.2 shows the schematic of the process used for these tests. However in this test series the heat exchanger was not operating.

Microwave energy was applied which slowly heated the water in the pipe heater. The water flow rate was increased slowly during the heating up period to keep the water temperature under steady control. The flow rate was increased up to a point where the temperature stabilised at 112°C. Three sets of test data were taken at this temperature and are tabulated in Table 6.2.

To remove air pockets from the pipe heater, the entire unit was tilted with the U bend of the pipe heater being lower than the rest of the pipe system. In this configuration any small air pockets in the system gathered at the reducers. This effectively formed a reservoir at the pipe heater end. Because of the low flow rate and the laminar temperature separation of heated liquids, thermocouple T_2 showed a high reading, significantly higher than T_3. This effect was not observed when trialling with sludge because of the viscous nature of sludge which resulted in plug flow.

Observations of the pumping rate of the two peristaltic liners was possible via the sight glasses. Testing revealed the level of water in the system was constant over a period of time. This showed that both peristaltic liners were synchronised in their flow rates.

Table 6.2 Observed results for tap water

Run	1.	2.	3.
Power kW			
Total	44.2	44.7	44.5
Microwave	29.5	29.5	29.5
Magnetrons mA	6@950	6@950	6@950
Temperatures °C			
T1	20	20	20
T2	94	100	97
T3	80	82	90
T4	112	112	112
T5	91	101	100
Ambient	24	24	24
Waveguide	43	45	48
Cool. Water In	23	24	24
Out	26	27	27
Pressure kPa			
P2	50	50	50
P4	50	50	50
Flow rate kg/min	2.7	3.24	3.39
Mic. Efficiency %	59	71	74

6.3 Testing at Shellharbour Sewage Treatment Plant

6.3.1 Aim

The aim of these tests were to determine what level of treatment was required to process sludge to levels of pasteurisation and sterilisation using the microwave pipe heater. Two parameters were used to evaluate the process,

- the maximum temperature attained by the sludge,
- residence time at temperature.

Microbiological samples were sent to Fordham Laboratories Pty Ltd for analyses for three types of pathogens (Appendix E),

- Faecal coliforms,
- Escherichia coli (E. coli),
- Salmonella.sp. (salmonella)

Total plate counts were also determined to give an indication of the bacteria present. Pasteurisation was achieved when zero counts of pathogens were recorded, and sterilisation was achieved when 10 or less organisms per gram for total plate count as well as zero counts for pathogens were recorded. Much of the work was centered around developing appropriate parameters for sterilisation and once established, treatment temperatures were lowered to evaluate the most economic parameters for pasteurisation. At the time of testing, the Department of Health did not have guidelines for the heat pasteurising or sterilising of sludge so the species analysed were on recommendations from professionals in the field of microbiology.[29]

An analysis of the effectiveness for the pipe heater, process and plant were also investigated: Equation 4.18a was used to calculate heat transfer to the sludge. The results are discussed in detail in the Chapter 7. The terms used in this discussion are defined as,

- the microwave transfer effectiveness. This is the ratio of the measured temperature rise of the sludge through the pipe heater section only (i.e. T_4 - T_2), to the microwave power level.

- the process effectiveness. This is similar to the microwave transfer effectiveness although it incorporates the temperature rise through the heat exchanger as well as the pipe heater (i.e. T_4 - T_1).

- the plant effectiveness. This is similar to the process effectiveness although it uses the total power into the plant instead of the microwave power.

6.3.2 Commissioning of Plant

The sludge processing plant was taken to Shellharbour in February 1989. The system was successfully installed and a test run with water showed everything was running correctly. The next day the unit was to be tested again using water. However during this run the teflon liners developed leaks and filled several waveguides with water. Leakage problems resulted in a complete strip down of all pipe heater sections and the discovery that carbon rubber seals used in the system had reacted with the microwave energy. The rubber seals were replaced with silicone sealant but this proved unsatisfactory with further leakage into two waveguides. In an attempt to seal these leaks, a mixture of plaster and cement was pumped through the system under pressure but this also proved to be unsuccessful.

A complete redesign of the teflon liner seals was undertaken to allow forced sealing under pressure. The seals proved effective and testing was able to recommence in April 1989. The seals did leak a little but drain holes were drilled in the pipe sections to allow the leaking droplets of water to drain so as to not hinder testing.

A summary of results is given in Table 6.3 and observed results are given in Tables 6.4 to 6.9. Biological reports on the samples taken are shown in Appendix G. Residence time is considered to be the time the sludge was near or at maximum temperature and pressure until it exited the second pump liner. Maximum temperature is regarded as the estimated average maximum temperature the sludge attained. In many cases when taking temperatures, an upper and lower value is quoted. However, an estimate of the average temperature is considered for analysing results which is shown in brackets "( )".

6.3.2.1 First Test Run - 12/4/89

The first tests were run on 12th April with a fixed energy input of 39.4kW and various sludge flow rates. Table 6.4 shows the observed results and Figure 5.2 shows the schematic of the system used. Sludge was fed into the system via a hopper mounted on the inlet of the pump. Water was mixed with the sludge to enable it to flow into the pump and this mixing was done manually in the hopper. During the first run, it was noted temperature and pressure measurements were very unstable, with changes occurring quite rapidly. During testing, a blockage at the inlet of the pump resulted in no sludge flow and the system exceeded 400kPa and 140^{o}C. This resulted in the exit sight glass breaking.

The sight glasses were installed to allow observation of the sludge flow and although useful, they were not essential to the system operation and were removed. After their removal and tests re-run, it was quickly appreciated that variations in sludge water content, (ie, the consistency of the sludge mix), had caused the erratic pressure and temperature fluctuations.

Each test to this stage had been run with sludge being mixed in the feed hopper by various operators taking turns to shovel and mix the sludge and water until a free running sludge was achieved. Each batch was different, resulting in sludge flow changes through the pipe cavities, which in turn led to fluctuations in temperature and pressure measurements.

For the system to operate under reasonably standard conditions, the sludge was mixed in a holding tank (a 9 cubic metre skip) prior to it being drawn into the delivery peristaltic pump . This tank ensured sludge homogeneous sludge consistency over an eight hour test period. The most effective method of mixing was found to be the use of a post-hole digger with a large diameter auger. Mixing the sludge with this device also revealed the material has remarkable bridging characteristics. In particular the sludge refused to "turn over" until water content reached around 85%W.B. In all subsequent tests, sludge was drawn directly from the bottom of the skip as shown in Figure 6.2.

Flow rate measurements were very difficult to measure when the outlet pump temperature exceeded 100^{o}C. Hence, a relationship between the flow rate versus the variable speed drive frequency used to control the speed of the pump, was determined for cold sludge pumped through the system at a moisture of 85%WB (Figure 6.3). Considering the sludge moisture content was around 85%WB for all tests, this chart was assumed to be correct for all flow rate predictions except for the sixth test run which is discussed later.

6.3.2.2 Second Test Run - 21/4/89

The second series of tests were run on 21st April with a steady sludge flow and various microwave energy levels (Table 6.5). Operating temperatures in the system were held high and the resulting residence time was also extended to above 10 minutes to ensure conditions were such that sterilisation should be achieved. Samples taken for analyses showed total or near total sterilisation was achieved for each treated sample.

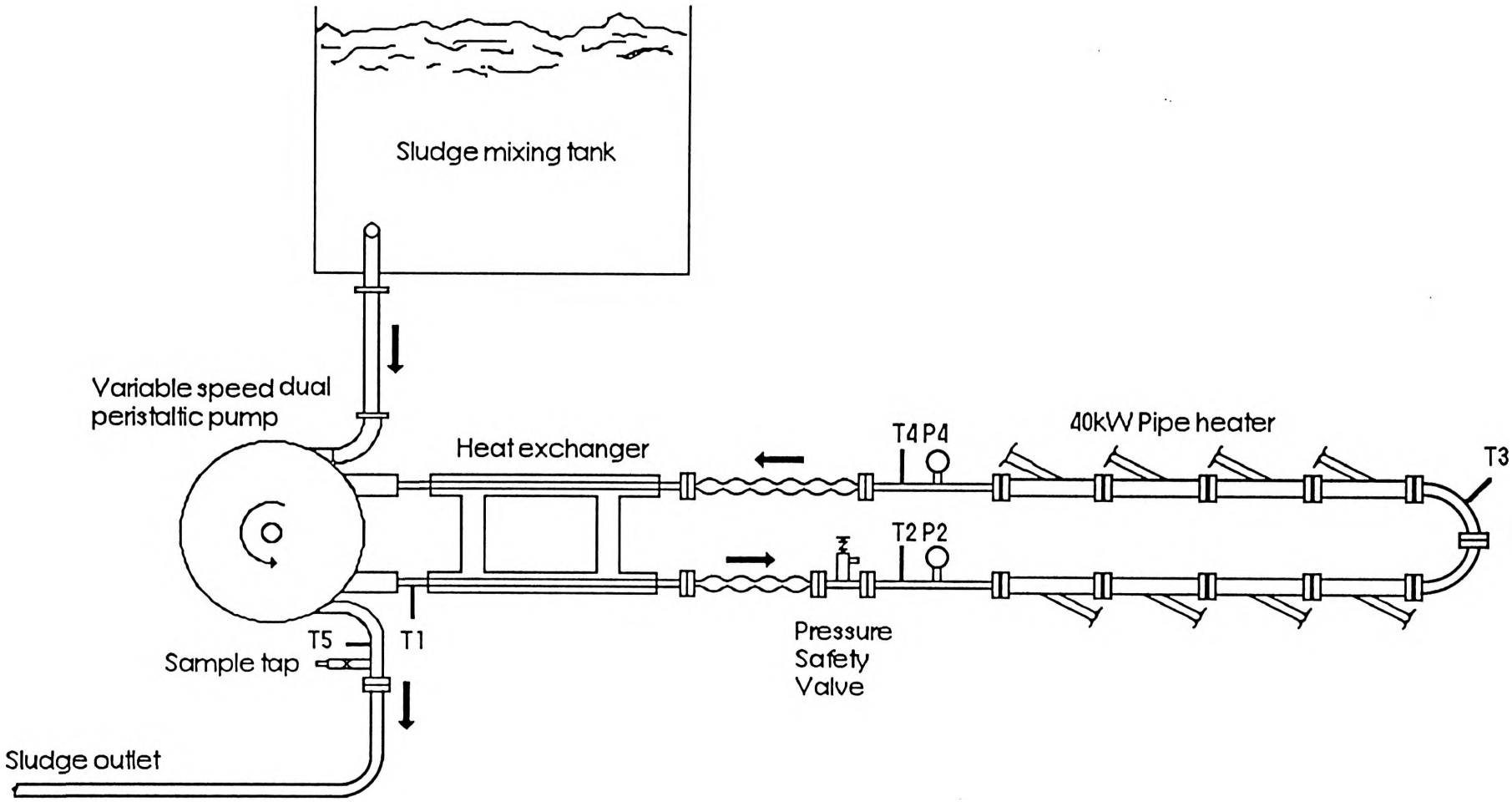
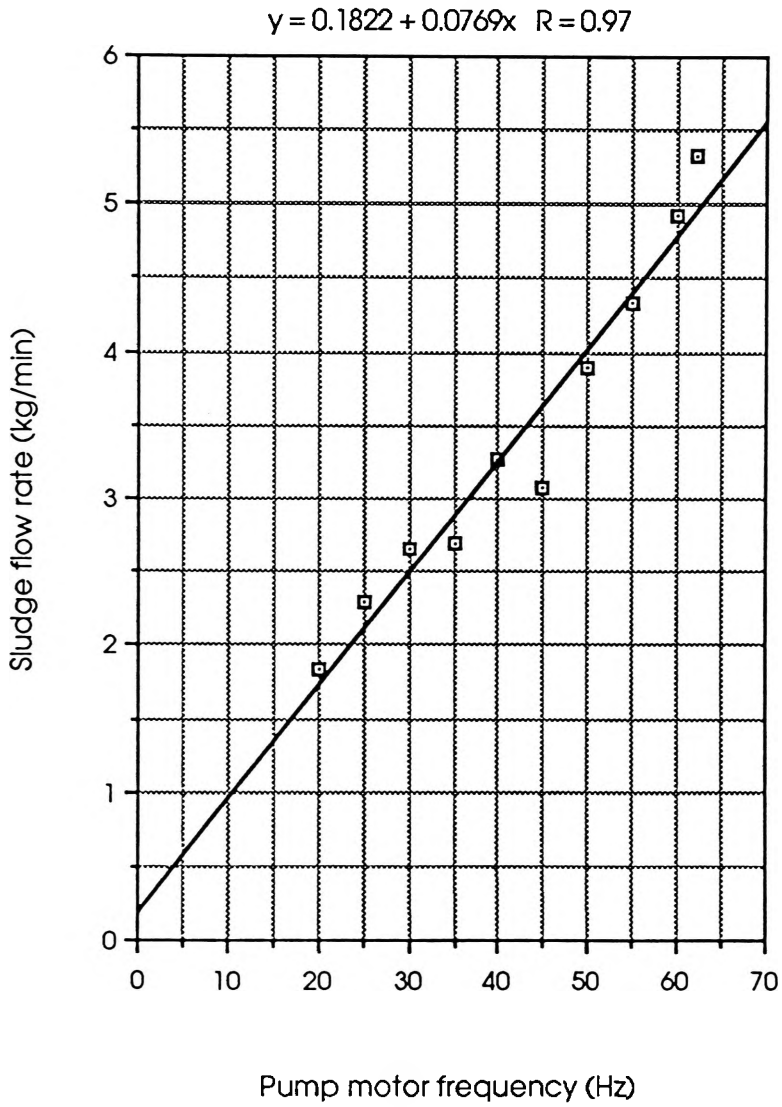


Figure 6.2 Schematic of system for the majority of the test runs

Figure 6.3 Flow rate chart



Following this successful run two subsequent test series were planned. Namely, one with a constant flow rate and changing energy input and a second run with fixed energy input and changing flow rate. Preparation runs showed unusually high pressures were being registered by the cold pumping of sludge. After some time it was found that the cement and plaster used earlier in an attempt to seal the leaks at the start of trials had not been completely removed and some had dislodged and clogged the exit reducer. This fact is mentioned because it is believed it may have played a role in achieving the high levels of sterilisation in this test. The reason for this is explained below.

It was also observed that the temperature of the sludge was much higher in the upper half of the pipe heater than in the lower. The variation was as much as 40^{o}C. In our test system all microwave energy is introduced to the top of the pipe where it was apparently being rapidly absorbed by the sludge. As there was no physical mixing taking place in the pipe due to plug flow, the sludge developed a temperature differential from top to bottom. The immediate solution to this problem was the installation of a simple mixer plate at the U-bend.

The previously mentioned clogging of the outlet stage of the process pipe could have acted as a temperature equalisation point for the sludge. Sterilisation was achieved for each of the samples and this may have been due to all the sludge reaching a consistent temperature of around 120^{o}C and an appropriate residence time prior to exit.

6.3.2.3 Third Test Run - 4/5/89

The third test run on 4th May had short residence times with an appropriate high exit temperature of 103°C (Table 6.6). Both samples showed high total plate count for bacteria, but full destruction of faecal coliforms, E. coli and salmonella. It is interesting to note that the samples of treated sludge from this run were left for one week on the shelf before laboratory analysis was performed. No regrowth in the faecal coliforms, E. coli or salmonella occurred. However a regrowth in the bacteria plate count could have occurred and this may explain the high count.

At this time a second sample tap was added 16 metres downstream from the first to provide results for a longer residence time. All the results from this sample point showed contamination which was assumed to be due to a residue of untreated sludge in this length of pipe and a failure to effectively heat treat this "low temperature" section while testing. As a result, all test samples from this second sample point have been disregarded.

6.3.2.4 Fourth Test Run - 10/5/89

The results of this test run showed samples 1 & 2 were at appropriate temperature, pressure and residence time to achieve sterilisation, and yet, total plate count remained mysteriously high, (Table 6.7). The overall results continued to show the trend of an increasing bacteria count as treatment temperatures and pressures reduced. In samples 6 and 7 there were traces of faecal coliforms and E. coli at temperatures of 95°C However this would most probably be because of the short residence times (below 5 minutes) for both these samples.

6.3.2.5 Fifth Test Run - 11/5/89

This test run had to be terminated after the first set of samples were taken due to problems on the suction side of the pump (Table 6.8). However, the results showed complete sterilisation at 132°C and 3 minutes 32 seconds residence time. Results from the second sample tap have been disregarded as explained above.

6.3.2.6 Sixth Test Run - 16/5/89

This test run again showed sterilisation conditions were achieved, even though residence times were short (Table 6.9). The total plate count increased as the temperature and pressure of the system reduced. The increasing residence time recorded was due to the gradual reduction in microwave power input (magnetrons were gradually switched off from the exit end of the pipe heater). Faecal coliforms, E. coli and salmonella were not detected even down to a temperature of 66°C.

When analysing the effectiveness of the process for this run, most of the calculated effectiveness were well the range of the earlier results. The likely explanation must lie in the use of the flow rate calibration chart for the flow prediction. The average solids content measured for this test run were calculated to be 16.35% which must have been somewhat excessive. However, to enable meaningful comparison of these results with the other results, a correction factor of 0.6 was applied to the flow rate calibration chart. This in turn adjusted the residence time and calculated effectiveness in line with all the other tests to yield realistic results. The corrected results are used for analysis, Table 6.3, and shown in parenthesis "{ }" in Table 6.9.

Table 6.3 Summary of Results

	Max Temp (°C)	Residence Time (min sec)	Plate Count (ogs/g)	Faecal Col. (MPN)	E. coli (MPN)	Salm'a (/25g)	Effectiveness Mic. (%)	Proc's (%)	Plant (%)
First test run - 12/4/89									
1	100	3m 52s	NA	ND	ND	ND	55.8	56.8	36.1
2	116	4m 42s	$7.7x10^3$	ND	ND	ND	53.6	56.6	35.9
3	118	4m 11s	$1.9x10^4$	ND	ND	ND	61.8	64.5	41.5
4	119	4m 26s	$4.1x10^3$	ND	ND	ND	58.5	61.6	39.7
5	140	4m 42s	$4.4x10^4$	ND	ND	ND	65.1	70.3	45.6
Second test run - 21/4/89									
1	122	10m 55s	25	ND	ND	ND	70.6	78.7	48.8
2	126	10m 55s	5	ND	ND	ND	59.0	66.8	46.4
3	127	10m 55s	5	ND	ND	ND	59.7	67.5	46.6
Third test run - 4/5/89									
1	120	4m 11s	$>10^7$	ND	ND	ND	58.9	63.9	44.4
2	117	3m 53s	$>10^7$	ND	ND	ND	62.7	67.7	47.0
Fourth test run - 10/5/89									
1	129	8m 0s	$2.8x10^3$	ND	ND	ND	59.8	65.3	41.7
2	124	7m 9s	$4.6x10^3$	ND	ND	ND	64.0	69.9	44.9
3	114	6m 3s	$1.9x10^5$	ND	ND	ND	70.1	74.7	48.4
4	110	5m 24s	$4.4x10^5$	ND	ND	ND	76.0	80.3	52.1
5	107	5m 0s	$4.6x10^5$	ND	ND	ND	79.3	84.0	54.8
6	95	4m 33s	$9.3x10^5$	46	24	ND	78.0	80.1	52.2
7	92	4m 10s	$1.0x10^6$	>240	>240	ND	81.8	84.0	54.9
Fifth test run - 11/5/89									
1	132	3m 32s	10	ND	ND	ND	78.6	86.2	58.6
Sixth test run - 16/5/89									
1	123	6m 10s	20	ND	ND	ND	64.3	70.3	44.0
2	112	7min 45s	5	ND	ND	ND	68.3	74.7	46.4
3	100	7m 45s	$3.7x10^4$	ND	ND	ND	68.1	71.9	43.7
4	87	9m 5s	$4.7x10^5$	ND	ND	ND	76.7	79.6	48.7
5	78	9m 5s	$6.1x10^5$	ND	ND	ND	62.3	65.7	39.4
6	66	9m 53s	$2.1x10^6$	ND	ND	ND	56.1	60.0	35.2

NA - not available

ND - not detected

Table 6.4 First test run - 12/4/89 - Results

Run	1.	2.	3.	4.	5.
Time	12.40pm	1.00pm	1.15pm	1.40pm	2.05pm
Power kW					
Total	62	62	61.3	61.1	60.8
Microwave	39.4	39.4	39.4	39.4	39.4
Magnetrons mA	8@950	8@950	8@950	8@950	8@950
Temperatures °C					
T1	20	20	20	20	20
T2	22	25	24	25	29
T3	89/90	105/110	101/105	107/112	142/146
T4	94/100 (100)	114/121 (116)	116/121 (118)	115/124 (119)	138/143 (140)
T5	86/87	99	98/99	102/103	99/109
Ambient	23	23	23	24	24
Waveguide	52	58	58	59	60
Cool. Water In	25	24	24	25	25
Out	27	27	27	27	27
Pressure kPa					
P2	160	195	190	205	400
P4	140	185	170	190	400
Motor Freq. Hz	49.7	40	45	42.5	40
Flow rate kg/min	4.0	3.3	3.7	3.5	3.3
Res.Time at Temp.	3m 52s	4m 42s	4m 11s	4m 26s	4m 42s
Effectiveness %					
Microwave	55.8	53.6	61.8	58.5	65.1
Process	56.8	56.6	64.5	61.6	70.3
Plant	36.1	35.9	41.5	39.7	45.6
Treated Sample	4	6	10	12	16
Plate Count	NA	7.7×10^3	1.9×10^4	4.1×10^3	4.4×10^3
Faecal Coliforms	ND	ND	ND	ND	ND
E. coli	ND	ND	ND	ND	ND
Salmonella	ND	ND	ND	ND	ND

Comments

10% solids content (wet basis) - approx
Exit sight glass leaking (run 1)
Exit sight glass exploded (run 6)
Sludge fed manually into pump via hopper
Water added to allow easy feeding to pump

Untreated Sample	2	8	14	Refer to letter 24th April 1989
Plate Count	NA	NA	NA	for analysis report
Faecal Coliforms	>2400	920	350	(Appendix E).
E. coli	>2400	920	350	NA - not available.
Salmonella	ND	ND	ND	ND - not detected.

Table 6.5 Second test run - 21/4/89 - Results

Run	1.	2.	3.	
Time	1.47pm	3.05pm	3.20pm	
Power kW				
Total	33.4	37.3	37.5	
Microwave	20.7	25.9	25.9	
Magnetrons mA	R 4@950	R 4@950	R 4@950	
	L 4@ 50	L 3@300	L 3@300	
Temperatures °C				
T1	25	23	23	
T2	35	35	35	
T3	126	132	130	
T4	122 (122)	121/128 (126)	127 (127)	
T5	109	99/105	118	
Ambient	22	22	22	
Waveguide	32	38	40	
Cool. Water In	20	20	20	
Out	21	22	22	
Pressure kPa				
P2	200	200	200	
P4	160	200	200	
Motor Freq. Hz	28.1	28.0	28.0	
Flow rate kg/min	2.4	2.4	2.4	
Res.Time at Temp.	10m 55s	10m 55s	10m 55s	
Effectiveness %				
Microwave	70.6	59.0	59.7	
Process	78.7	66.8	67.5	
Plant	48.8	46.4	46.6	
Treated Sample	2	3	4	5
Plate Count	$2.5x10^1$	$0.5x10^1$	<10	$0.5x10^1$
Faecal Coliforms.	ND	ND	ND	ND
E. coli	ND	ND	ND	ND
Salmonella	ND	ND	ND	ND
			(Two samples taken)	

Comments: 14.5 % solids content (wet basis).
L3 shut down after run 1.
Sludge pumped directly out of bottom of skip.

Untreated Samples	1
Plate Count	$4.1x10^8$
Faecal Coliforms.	>>2400
E. coli	>>2400
Salmonella	present

Refer to letter 2nd May 1989 for analysis report (Appendix E).
ND - not detected

Table 6.6 Third test run - 4/5/89 - Results

Run	1.		2.		
Time	11.40am		12.08pm		
Power kW					
Total	56.6		56.6		
Microwave	39.3		39.3		
Magnetrons mA	8@950		8@950		
Temperatures °C					
T1	23		22		
T2	31		29		
T3	94		85		
T4	111? (120)		117 (117)		
T5	103		102		
Ambient	22		22		
Waveguide	48		49		
Cool. Water In	22		22		
Out	24		25		
Pressure kPa					
P2	240		200		
P4	200		160		
Motor Freq. Hz	50		55		
Flow rate kg/min	3.7		4.0		
Res.Time at Temp.	4m 11s		3m 53s		
Effectiveness %					
Microwave	58.9		62.7		
Process	63.9		67.7		
Plant	44.4		47.0		
Treated Sample	A-1	A-2	B-1	B-2	Refer to letter dated 18th May
Plate Count	$>10^7$	$1.4x10^8$	$>10^7$	$>10^6$	1989, for analysis report
Faecal Coliforms	ND	ND	ND	4.3	(Appendix E).
E. coli	ND	ND	ND	4.3	ND - not detected
Salmonella	ND	ND	ND	ND	

Comments

14.5% solids content (wet basis).
Sludge pumped directly out of bottom of skip.
Additional sample tap placed 16 metres downstream of first.
Samples were left on shelf for 5 days before analysis.
No untreated samples taken.

Table 6.7 Fourth test run - 10/5/89 - Results

Run	1.	2.	3.	4.	5.
Time	12.27pm	12.48pm	1.08pm	1.27pm	1.53pm
Power kW					
Total	47.0	46.7	46.3	46.2	46.0
Microwave	30.0	30.0	30.0	30.0	30.0
Magnetrons mA	6@950	6@950	6@950	6@950	6@950
	2@50	2@50	2@50	2@50	2@50
Temperatures °C					
T1	17	17	17	17	17
T2	27	26	23	22	22
T3	124/128	115	98/101	80/86	74
T4	126/132 (129)	124/125 (124)	106/114 (114)	94/113 (110)	106/108 (107)
T5	101/105	100/105	100	91	90
T6	96	93/95	87	83	82
Ambient	20	21	22	22	22
Waveguide	43	46	47	47	46
Cool. Water In	21	21	21	21	21
Out	23	23	23	23	23
Pressure kPa					
P2	230	180	130	120	120
P4	210	160	100	85	70
Motor Freq. Hz	30	35	40	45	50
Flow rate kg/min	2.5	2.8	3.3	3.7	4.0
Res.Time at Temp.	8m 0s	7m 9s	6m 3s	5m 24s	5m 0s
Effectiveness %					
Microwave	59.8	64.0	70.1	76.0	79.3
Process	65.3	69.9	74.7	80.3	84.0
Plant	41.7	44.9	48.4	52.1	54.8
Treated Sample					
Regular Tap	A-1	A-2	A-3	A-4	A-5
Plate Count	$2.8x10^3$	$4.6x10^3$	$1.9x10^5$	$4.4x10^5$	$4.6x10^5$
Faecal Coliforms	ND	ND	ND	ND	ND
E. coli	ND	ND	ND	ND	ND
Salmonella	ND	ND	ND	ND	ND
Downstream Tap	B-1	B-2	B-3	B-4	B-5
Plate Count	$3.4X10^5$	$>10^6$	$>10^6$	$2.5X10^7$	$6.1X10^5$
Faecal Coliforms	>240	4.3	ND	>240	>240
E. coli	>240	4.3	ND	>240	>240
Salmonella	ND	ND	ND	ND	ND

Table 6.7 Fourth test run - 10/5/89 - Results

(ctd...)

Run	6.	7.	
Time	2.22pm	2.35pm	
Power kW			
Total	46.0	45.9	
Microwave	30.0	30.0	
Magnetrons mA	6@950	6@950	
	2@50	2@50	
Temperatures °C			
T1	17	17	
T2	19	19	
T3	75	70/75	
T4	95 (95)	92/94 (92)	
T5	75	72	
T6	58	60	
Ambient	22	22	
Waveguide	45	46	
Cool. Water In	21	21	
Out	23	23	
Pressure kPa			
P2	110	100	
P4	50	90	
Motor Freq. Hz	55	60	
Flow rate kg/min	4.4	4.8	
Res.Time at Temp.	4m 33s	4m10s	
Effectiveness %			
Microwave	78.0	81.8	
Process	80.1	84.0	
Plant	52.2	54.9	
Treated Sample			
Regular tap	A-6	A-7	Refer to letter dated 18th May 1989,
Plate Count	$9.3x10^5$	$1.0x10^6$	for analysis report (Appendix E).
Faecal Coliforms	46	>240	ND - not detected.
E. coli	24	>240	
Salmonella	ND	ND	
Downstream Tap	B-6	B-7	
Plate Count	$>10^6$	$1.1x10^7$	
Faecal Coliforms	>240	>240	
E. coli	>240	>240	
Salmonella	ND	ND	

Table 6.7 Fourth test run - 10/5/89 - Results

(ctd...)

Comments	15.1% solids content (wet basis). L1 and L2 at low power. Sludge pumped directly out of bottom of skip. Insulated outlet hose and heat exchanger. Considerable temperatures fluctuations (run 4). Machine shut down due to blockage (run 6).	
Untreated Sample	Initial	Refer to letter dated 18th May 1989,
Plate Count	1.7×10^8	for analysis report (Appendix E).
Faecal Coliforms	>2400	
E. coli	>2400	
Salmonella	Present	

Table 6.8 Fifth test run - 11/5/89 - Results

Run	1.		
Time	2.37pm		
Power kW			
Total	58.0		
Microwave	40.0		
Magnetrons mA	8@950		
Temperatures °C			
T1	20		
T2	30		
T3	110/122		
T4	130/132 (132)		
T5	100/102		
T6	95		
Ambient	21		
Waveguide	44		
Cool. Water In	20		
Out	22		
Pressure kPa			
P2	280		
P4	260		
Motor Freq. Hz	55		
Flow rate kg/min	4.4		
Res.Time at Temp.	3m 32s		
Effectiveness %			
Microwave	78.6		
Process	86.2		
Plant	58.6		
Treated Sample	A-1	B-1	Refer to letter dated 30th May 1989,
Plate Count	1.0×10^1	$>3.0 \times 10^5$	for analysis report (Appendix E).
Faecal Coliforms	ND	ND	ND - not detected.
E. coli	ND	ND	
Salmonella	ND	ND	

Comments

13.7% solids content (wet basis).
Sludge pumped directly out of bottom of skip.
Insulated outlet hose and heat exchanger.
Having problems on suction side of pump.
No untreated samples taken.

Table 6.9 Sixth test run - 16/5/89 - Results

Run	1.		2.		3.	
Time	11.14am		11.33am		12.00pm	
Power kW						
Total	47.6		40.4		37.5	
Microwave	29.8		25.1		22.8	
Magnetrons mA	Right	Left	Right	Left	Right	Left
1	950	50	950	50	950	50
2	950	950	950	50	950	50
3	950	--	950	--	950	--
4	950	950	950	950	950	500
Temperatures °C						
T1	19		19		19	
T2	28		27		23	
T3	118/124		113/118		100/104	
T4	123 (123)		112 (112)		96? (100)	
T5	102/105		100/103		92/96	
T6	99		91		79	
Ambient	18		18		18	
Waveguide	29		29		28	
Cool. Water In	20		20		20	
Out	22		22		22	
Pressure kPa						
P2	230/260		160/180		100/110	
P4	220/230		130		60	
Motor Freq. Hz	60		60		60	
Flow rate kg/min	4.8 {2.88}		4.8 {2.88}		4.8 {2.88}	
Res.Time at Temp.	3m 42s {6m 10s}		4m 39s {7m 45s}		4m 39s {7m 45s}	
Effectiveness %						
Microwave	107.1 {64.3}		113.8 {68.3}		113.5 {68.1}	
Process	117.1 {70.3}		124.5 {74.7}		119.9 {71.9}	
Plant	73.3 {44.0}		77.4 {46.4}		72.9 {43.7}	
Treated Sample	A-1	B1	A-2	B-2	A-3	B-3
Plate Count	$2x10^1$	$2.5x10^3$	$0.5x10^1$	$1.8x10^3$	$3.7x10^4$	$1.8x10^5$
Faecal Coliforms	ND	ND	ND	ND	ND	$9.0x10^0$
E. coli	ND	ND	ND	ND	ND	$9.0x10^0$
Salmonella	ND	ND	ND	ND	ND	ND
Comments	L3 disconnected (run 1). Machine tripped out at 11.45am. Results in parenthesis "{ }" are corrected, refer to text.					

Table 6.9 Sixth test run - 16/5/89 - Results

(ctd...)

Run	4.		5.		6.	
Time	12.17pm		12.38pm		12.52pm	
Power kW						
Total	33.5		30.2		26.9	
Microwave	20.5		18.1		15.8	
Magnetrons mA	Right	Left	Right	Left	Right	Left
1	950	50	950	50	950	50
2	950	50	950	50	950	50
3	950	--	950	--	950	--
4	950	50	500	50	50	50
Temperatures °C						
T1	19		19		19	
T2	22		22		22	
T3	101/103		86		74	
T4	87 (100)		78 (78)		66 (66)	
T5	84		75		66	
T6	75		68		62	
Ambient	18		19		19	
Waveguide	28		27		27	
Cool. Water In	19		19		19	
Out	20		20		20	
Pressure kPa						
P2	100/110		120/150		130/160	
P4	50		80		60/70	
Motor Freq. Hz	60		60		60	
Flow rate kg/min	4.8 (2.88)		4.8 (2.88)		4.8 (2.88)	
Res.Time at Temp.	5m 27s (9m 5s)		5m 27s (9m 5s)		5m 56s (9m 53s)	
Effectiveness %						
Microwave	127.8 (76.7)		103.9 (62.3)		93.5 (56.1)	
Process	132.7 (79.6)		109.5 (65.7)		100.0 (60.0)	
Plant	81.2 (48.7)		65.6 (39.4)		58.7 (35.2)	
Treated Sample	A-4	B-4	A-5	B-5	A-6	B-6
Plate Count	4.7×10^5	3.4×10^5	6.1×10^5	4.0×10^5	2.1×10^6	6.4×10^5
Faecal Coliforms.	ND	ND	ND	4.0×10^0	ND	1.1×10^6
E. coli	ND	ND	ND	4.0×10^0	ND	1.1×10^3
Salmonella	ND	ND	ND	ND	ND	ND
Comments	Results in parenthesis "{ }" are corrected, refer to text.					

Table 6.9 Sixth test run - 16/5/89 - Results

(ctd...)

Untreated Sample	1	2	Refer to letter dated 30th May
Plate count	$2.8x10^8$	$2.2x10^8$	1989, for analysis report
Faecal Coliforms	$>2.4x10^3$	$>2.4x10^3$	(Appendix E).
E. coli	$>2.4x10^3$	$>2.4x10^3$	ND - not detected.
Salmonella	present	present	

Moisture		
	#1	- 17.6% solids content (wet basis)
	#2	- 15.1% solids content (wet basis)
	Supplied sludge	- 24.6% solids content (wet basis)

7. Discussion of Results

7. Discussion of Results

7.1 Heating Rate of Sludge

Results for the heating rate of sludge at varying solids content in comparison to water (Table 6.1 & Figure 6.1), revealed that at 2% solids content, the effective heat transferred to the sludge increased. An effectiveness of 102% was recorded at this solids content. However, as the solids content increased after 2%, the heating rate decreased. A fairly consistent heating rate was displayed from approximately 6.7 to 11.9% solids content, corresponding to an effectiveness of 85%. At solids content above 11.9%, the recorded heating rate decreased linearly to an effectiveness of 74% at 22.1% solids content.

It is interesting to note that at a solids content of roughly between 10 to 15%, the mixture of water and sludge changed from what could be classified as a thick slurry to a sludge. For the 16.7 and 22.1% sludge samples, the product could not be mixed and after heating, a temperature gradient was noticed with the hotter temperature being registered at the edges of the sample. This temperature gradient was also noticed in latter testing on the 40kW unit.

7.2 Water Tests

Tests using water on the 40kW unit showed that everything was operating correctly. There was a slight pulsation applied to the system due to the peristaltic action of the pump which registered on the pressure gauges. However the average of the range was considered to be the pressure of the system. The pressure of the system at 112°C

was 50kPa (gauge). A check with steam tables revealed that the temperature and pressure of the system corresponded with the saturation liquid point for water.

The microwave efficiency recorded for these tests on water varied from 59 to 74%. The lower efficiency for run 1 was due to high convective heat losses. These convective heat losses reduced and stabilised for run 2 and 3, which is shown by the resultant efficiencies.

7.3 Sludge Tests

7.3.1 Microbiological Analysis

Analysis of parameters and results given in Table 6.3 give an indication of the requirements for pasteurisation or sterilisation. The results were analysed using the maximum temperature of the sludge and the residence time at temperature. Various combinations can produce the same result. For the most economic combination of parameters, it is most appropriate to select the lowest temperature to which the sludge was to be heated, of which would demand a longer residence time.

This would result in greater pumping distances on the downstream side of the pipe heater which would in turn increase the pressure created in the pipe system. The safe maximum pressure of the system is governed by the mechanical limit of the teflon liners in the pipe heater which was discussed in Section 5.2.2. Hence, considering the working pressures for the tests conducted, it would not be possible to dramatically increase residence times to make the process more economic because the teflon liners would fail. However there is room for optimisation.

Analysis of the untreated sludge samples for all the tests conducted revealed consistently high contamination levels of faecal coliforms and E. coli. Salmonella was present in all untreated samples except mysteriously for untreated samples taken on the first test run. Total plate counts were very high in every case. In summary, all the untreated sludge was heavily contaminated with pathogens and bacteria, as was expected.

Figure 7.1 is a plot of the total plate count versus the temperature attained by the sludge. The trend of the plot shows a decreasing plate count corresponding to an increase in temperature. The exception to this is for samples taken on the third test run which show a very high plate count. However these samples were left on the shelf for one week before analysis and this delay before analysis could have resulted in a regrowth of bacteria.

Figure 7.2 shows a plot of temperature versus residence time indicating the effectiveness of the treatment in regards to sterilisation. Samples have been divided into three groups for analysis. Those samples that have been sterilised (a plate count of 10 or less), samples that are close to being sterilised (11 to 25 plate counts) and samples that are non-sterilised (plate count of over 25). Although not conclusive, there is a trend developing in obtaining parameters for sterilised sludge.

An estimate for complete sterilisation based on Figure 7.2 would correspond to a sludge temperature of 125°C and a residence time of at least 10 minutes. An equivalent temperature/time combination based on the fifth test run is 132°C at 3 minutes 32 seconds.

Figure 7.3 shows a plot of test parameters obtained for faecal coliforms, E. coli and salmonella. Salmonella was not detected in any of the treated samples. Hence all the parameters used for testing were sufficient to kill any traces of salmonella. However it is interesting to note that two samples found traces of faecal coliforms and E. coli (fourth test run; sample 6 & 7). Both samples had ample temperature as compared to other samples but residence times were too short to effectively kill all these pathogens. Results indicate that faecal coliforms and E. coli were destroyed at similar temperatures and residence times. This should be the case because they are from the same family type of pathogens.

There is insufficient results to accurately determine the minimum temperature/time parameters for pasteurisation at temperatures below 90°C. However, based on current test results, safe proposed treatment temperatures and residence times for pasteurisation using the pipe heater are,

- 66°C for at least 9 minutes 53 seconds, or
- 78°C for at least 9 minutes 5 seconds, or
- at least 95°C for residence times around 5 minutes.

Figure 7.1 Total plate count vs temperature

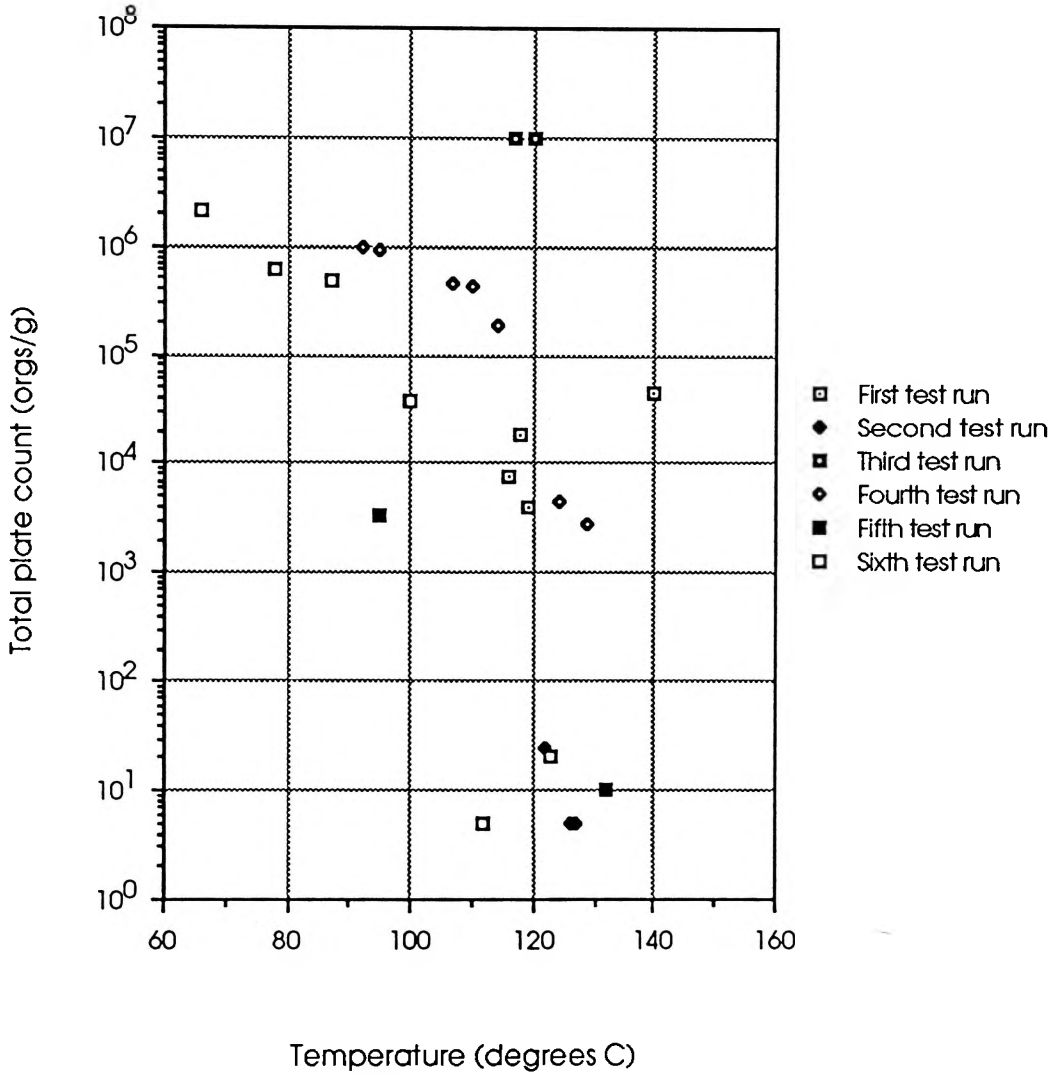


Figure 7.2 Temperature vs residence time indicating sterilisation

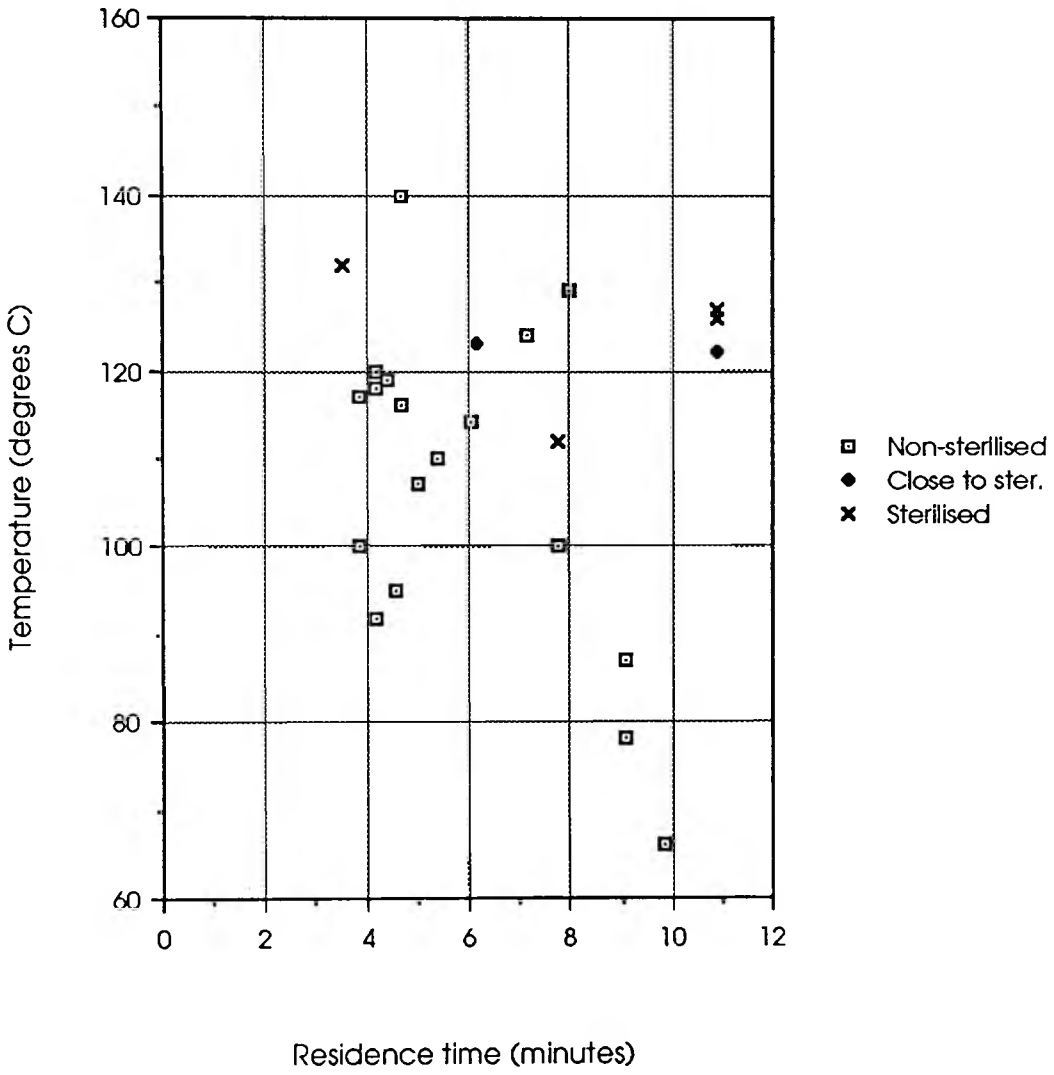
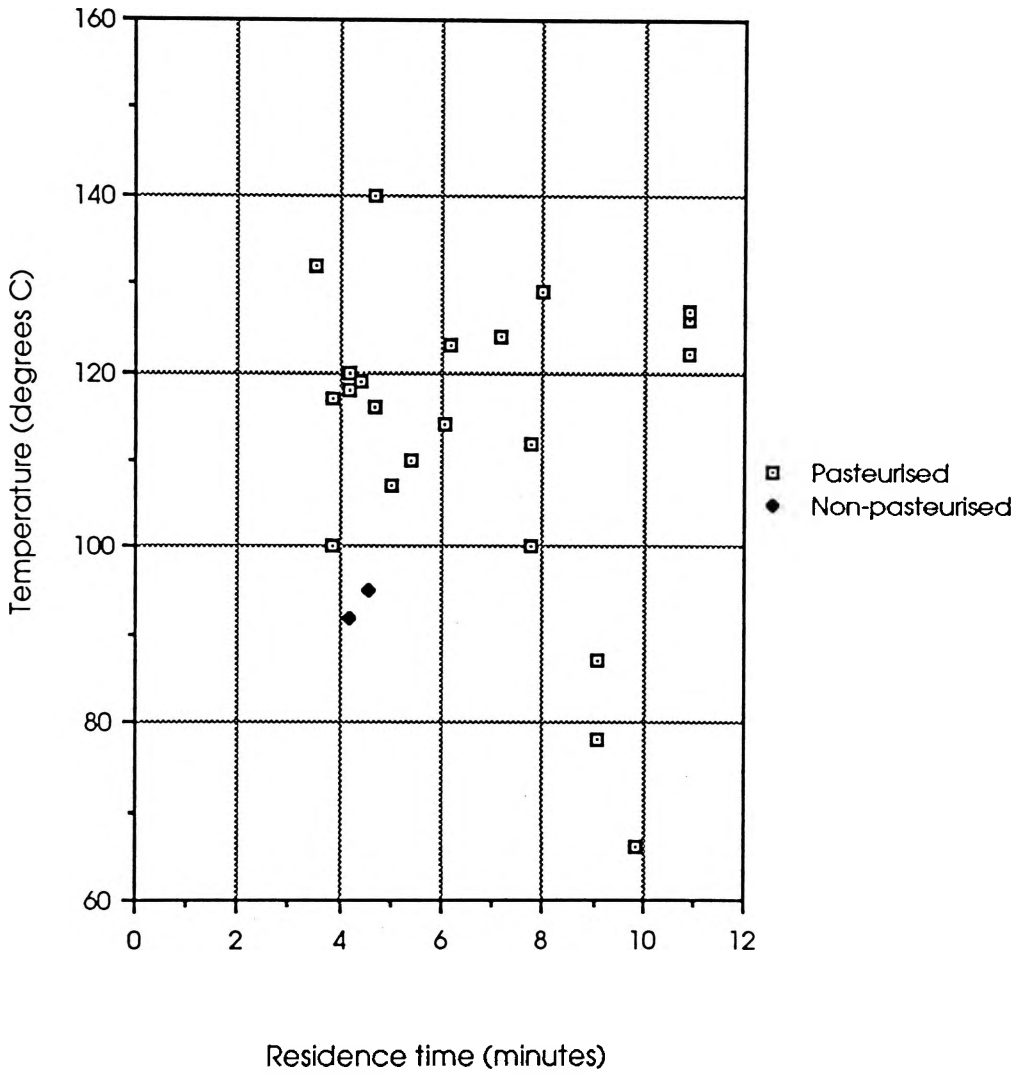


Figure 7.3 Temperature vs residence time indicating pasteurisation



7.3.2 Effectiveness Analysis

The microwave effectiveness for the plant operating on sewage sludge of moisture contents varying from 10 to 16.5% varied from 54 to 82% with an average effectiveness of 66%. Correspondingly, the process effectiveness varied from 57 to 84% with an average effectiveness of 71%. The relationship between process effectiveness and microwave effectiveness is shown in Figure 7.4.

Furthermore the plant effectiveness varied from 35 to 59% with an average effectiveness of 46%. The relationship between the plant effectiveness and the process effectiveness is shown in Figure 7.5. The process effectiveness is on average 55% higher than the plant effectiveness.

The heat exchanger on average, increased the microwave effectiveness by 5%. Considering the performance of the heat exchanger above 100°C, the average increase in effectiveness was 6% and below or equal to 100°C, the average effectiveness increase was 3%. Figure 7.6 shows a plot of the effectiveness increase with respect to the temperature of the sludge.

The microwave effectiveness was plotted against the sludge temperature although no trend could be determined from the plot (Figure 7.7) as considerable scatter of test results was observed. However there is a cluster of points around 120°C and 62% which may signify a typical microwave effectiveness for sludge heated to this temperature.

The microwave effectiveness was plotted against flow rate, although, again no trend could be determined from this plot (Figure 7.8).

Figure 7.4 Process vs microwave effectiveness

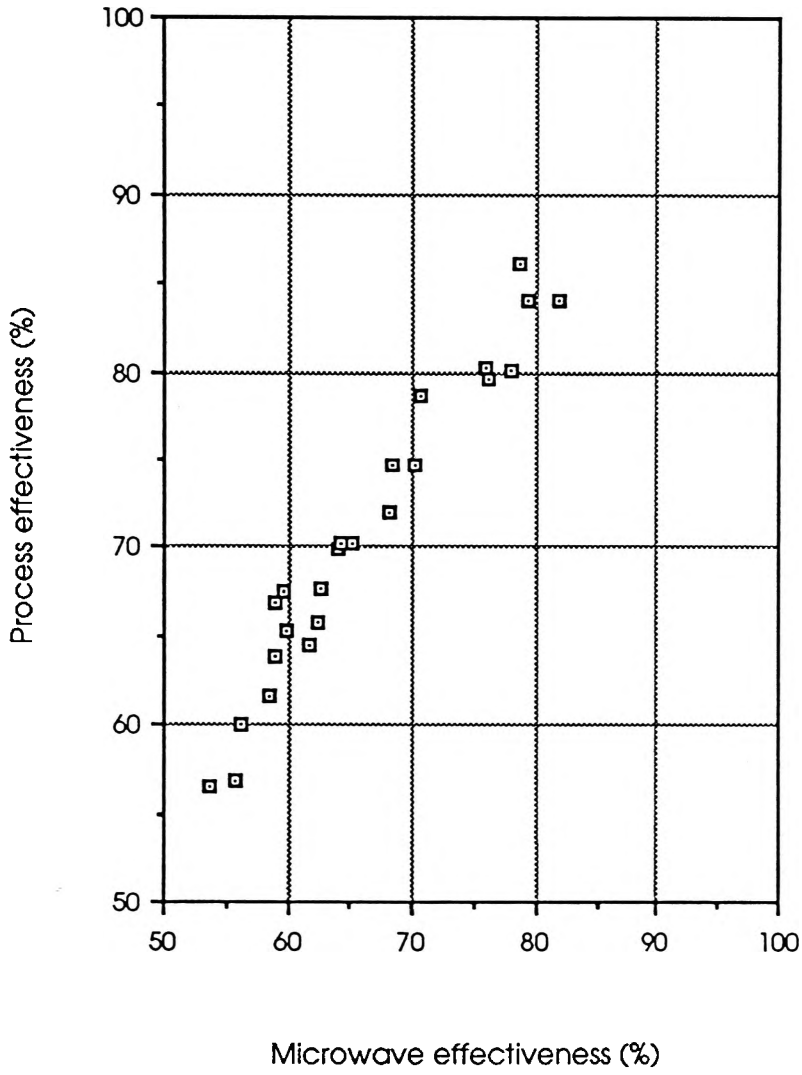


Figure 7.5 Plant vs process effectiveness

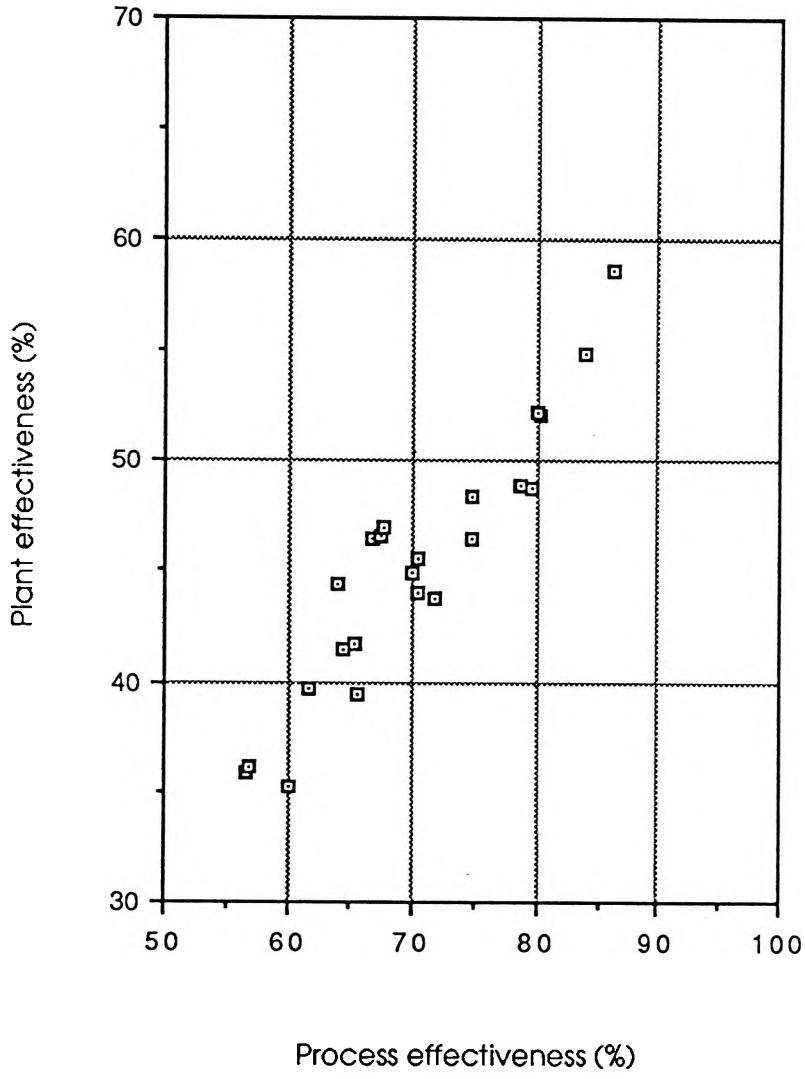


Figure 7.6 Effectiveness increase due to heat exchanger

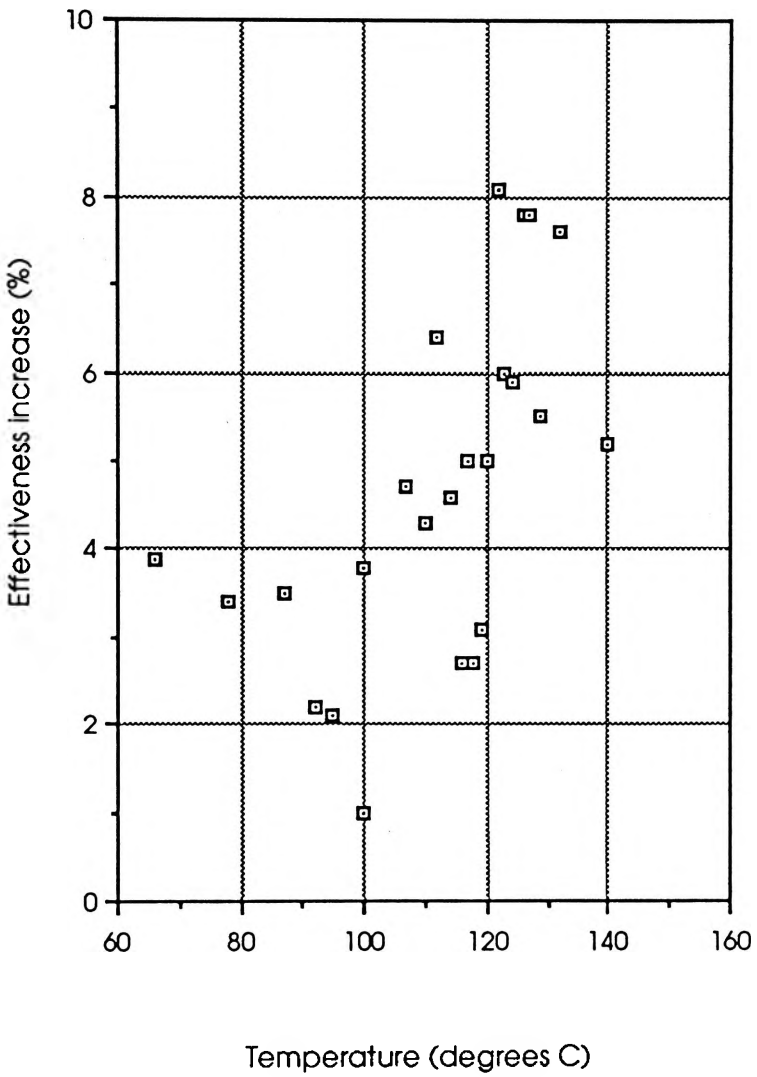


Figure 7.7 Microwave effectiveness vs temperature

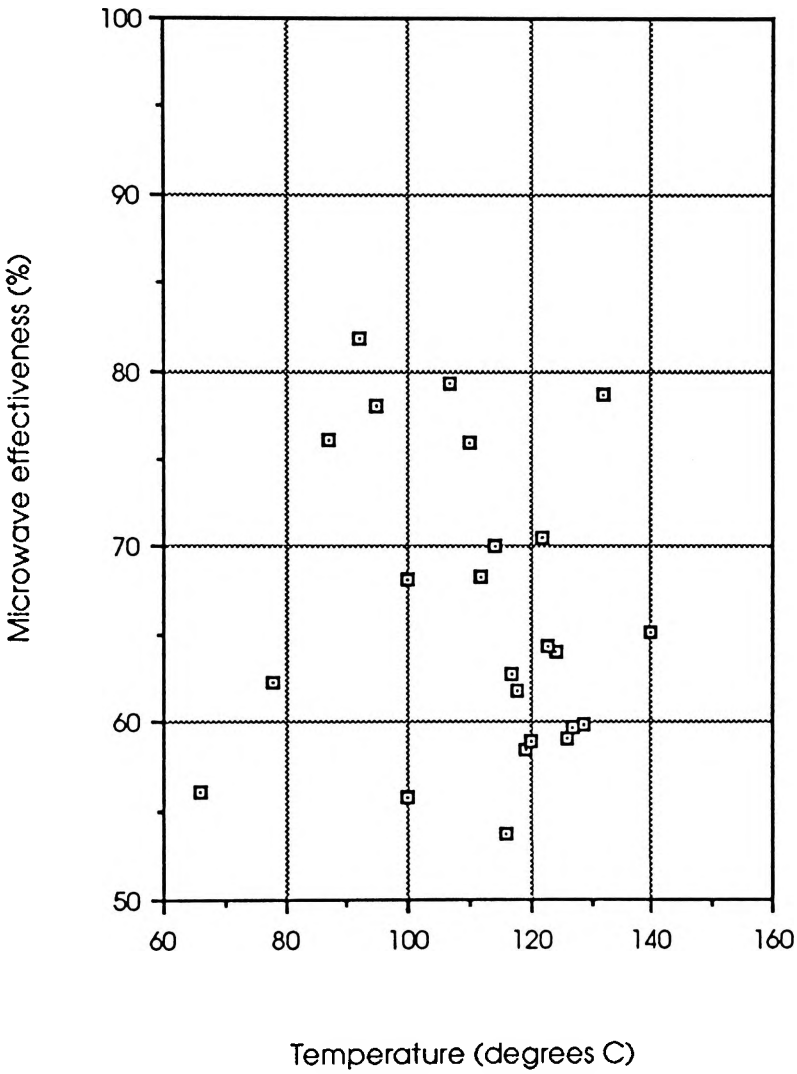
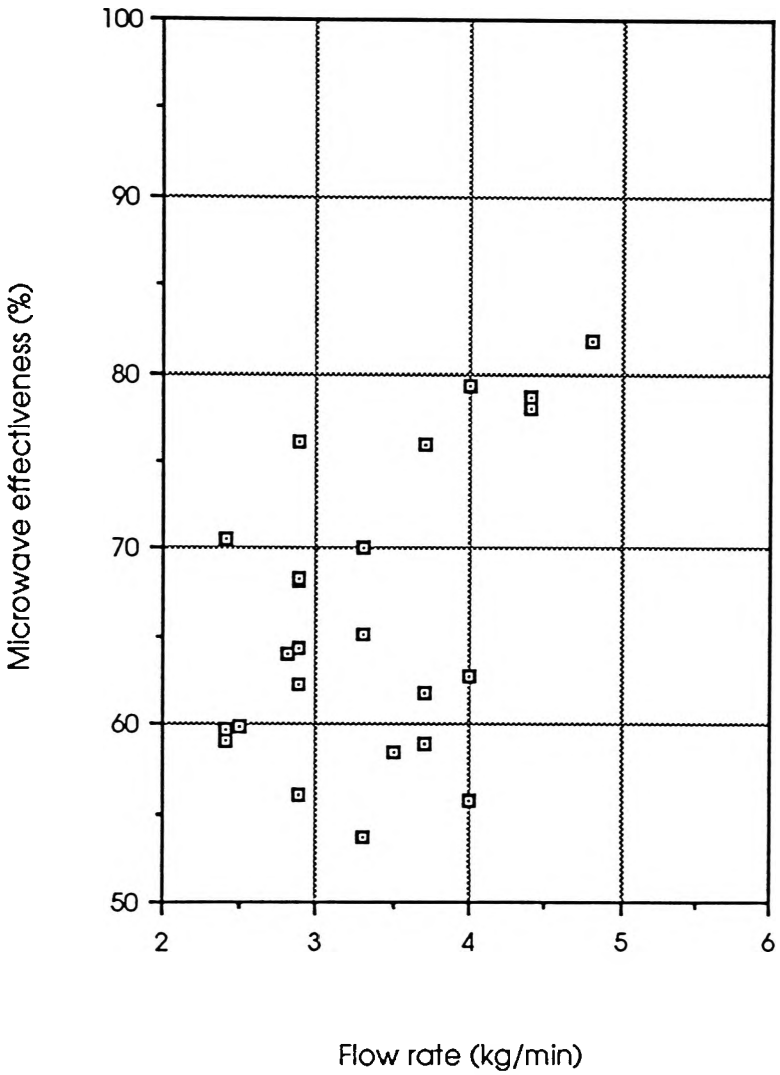


Figure 7.8 Microwave effectiveness vs flow rate



8. 60kW Pasteurisation Plant

8. 60kW Pasteurisation Plant

8.1 Introduction

The 40kW plant at Shellharbour Sewage Treatment Works demonstrated successfully the treatment of sewage sludge to levels of pasteurisation or sterilisation by using a continuous process. Results obtained from this experimental unit warranted further development, with the aim of commercialising the process. The Water Board purchased a dedicated 60kW sludge pasteurisation pilot plant from IMA, which was installed at Shellharbour for further evaluation.

Further testing was carried out by MARC on this plant to establish whether the plant that was presently running could produce sludge which met American EPA standard for Class A pathogen reduction.

This standard has proposed that, "when the temperature of sewage sludge has been raised (53°C for 5 days, 55°C for 3 days, or 70°C for one-half hour) and the density of faecal coliforms and faecal streptococci per gram of volatile suspended solids are equal to or less than 100, then class A pathogen requirements are achieved", (Appendix F). The aim of the microwave plant at Shellharbour is to heat sludge to temperatures higher than 70°C for a shorter period of time to achieve class A pathogen reduction. An outline of the 60kW plant along with the test results obtained from the plant are described in the following sections.

8.2 Description and Design of 60kW Plant

The design of the dedicated sludge pasteurisation plant incorporated up to a maximum of 60kW of microwave power applied using pipe heaters (Figure 8.1 & Photo 8.1 & 8.2). Power was applied by three banks of up to 20kW of microwave power. Each bank used four Philips YJ1600 magnetrons, hence there was a total of 12 magnetrons for the plant. Digital computer control, controlled the power output of each magnetron.

The computer control incorporated feedback of the sludge temperature, which, automatically adjusted the microwave power level of each bank to maintain the sludge temperature at a preset level at the end of each bank (T1, T2 & T3). However the monitored temperature was the outside pipe temperature which resulted in the sludge being hotter than actually measured due to the temperature loss through the steel pipe.

The plant was designed as a pasteurisation plant and hence did not incorporate any facility to enable the sludge to be heated above 100°C. Pumping of the sludge was achieved by the use of a plunger type positive displacement pump. The pump was located at the centrifuge and accepted dewatered sludge from the centrifuge. Either sludge from the digestion tank or sludge pumped from a nearby lagoon of the STP was used for processing (Photo 8.3). A pipe line carried the sludge on the positive side of the pump a distance of about 50 meters to the inlet of the 60kW plant. After microwaving, an insulated residence pipe minimised heat loss and maintained the sludge at temperature for certain residence time until the sludge was discharged.

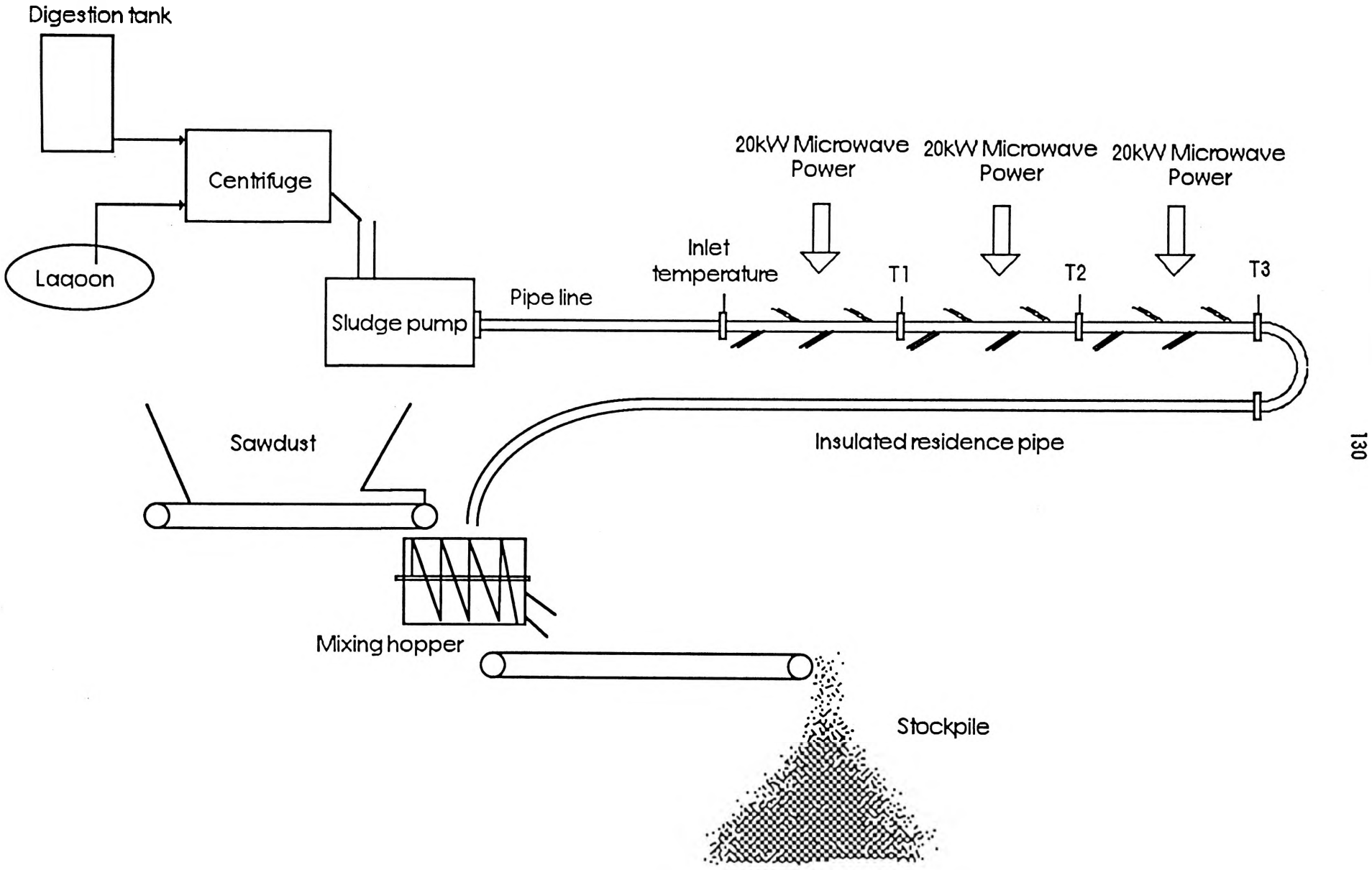


Figure 8.1 Schematic of 60kW microwave pasteurisation plant

After heat treatment, the sludge was discharged into a mixing hopper where it was mixed with sawdust and this mixture was taken via conveyor to a stockpile. The sawdust was mixed with the sludge to help dry the product (Photo 8.4).

Instrumentation of the plant incorporated,

- microwave power level of each bank,
- pipe temperature at the start of the first and the end of each bank,
- alarm conditions for fault diagnosis for the microwave power supply.

Inlet and exit sludge pressure instrumentation was also provided but where not operating.

8.3 Method of Analysis

Tests were conducted on this plant with the aim of determining an operating zone for Class A pathogen reduction. On advice from professionals, additional indicator species were analysed for and are summarised below,[30]

- Faecal coliforms,
- Escherichia coli, (E. coli)
- Faecal streptococci,
- Salmonella sp. (salmonella)

Microbiological testing was undertaken by Biological & Chemical Analysis Services (BACAS) University of Wollongong.

Two parameters were used to evaluate the process (similar to previous results for the 40kW unit),

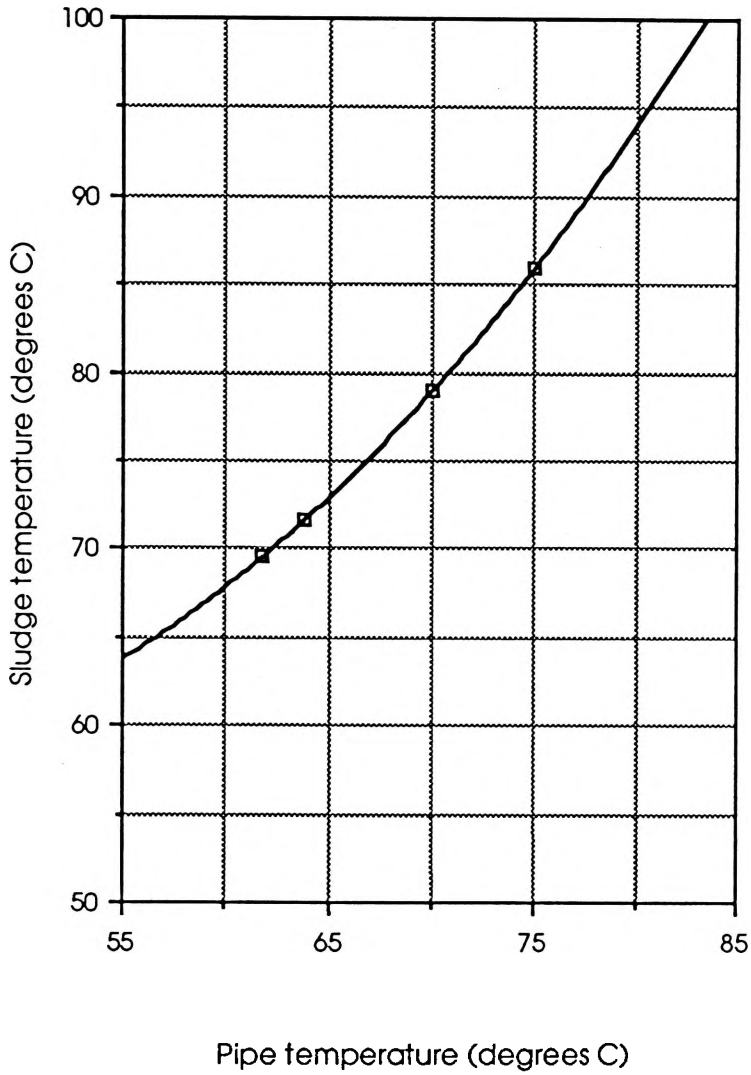
- maximum temperature of the sludge,
- residence time of the sludge at temperature.

For accurate analysis, the outside pipe temperature was corrected to the actual sludge temperature. This was achieved experimentally by installing a temperature probe inside the pipe at the end of the third bank (referred to as "T3 actual" in results) and the actual sludge temperature was monitored in reference to the pipe temperature. The correlation is shown in Figure 8.2. The actual sludge temperature is considered for all analyses and discussion of results.

The flow rate was simply measured by timing the required time to fill a bucket with sludge and then weighing the bucket. The residence time at temperature is based on the mass flow rate of the sludge and mathematically determined considering the volume of the residence pipe. The residence pipe is the length of pipe just after where the sludge was last heated by the microwaves to where the sludge exits the residence pipe. In most cases the residence pipe starts at the end of the third bank (refer Figure 8.1). However in a few cases no power was applied by the third bank and hence the residence pipe is considered to start at the end of the second bank.

Effectiveness calculations were also conducted for the process and are discussed later. The theoretical throughput for the plant has also been determined.

Figure 8.2 Sludge temperature vs outside pipe temperature



8.4 Results

Four test runs in total were conducted. For the first and second run, the sludge temperature was varied at a set sludge flow rate. For the third and fourth run, the temperature was set at what was considered to be appropriate for pasteurisation with sampling conducted every half hour over a period of time. A summary of results is given in Table 8.1 and observed results are presented in Tables 8.2 to 8.5. Faecal streptococci testing was not performed for the first two runs because of difficulty in obtaining specific analysing solution for that species. Microbiological analysis reports for the samples taken are shown in Appendix G. Sampling consisted of,

- treated samples, taken at the discharge of the residence pipe,
- untreated samples, taken before the sludge entered the sludge pump,
- treated samples mixed with sawdust, taken just after the mixing hopper,
- sludge/sawdust compost samples, taken from the stockpile.

8.4.1 First Test Run - 25/6/90

The first tests on 25/6/90 were conducted on sludge pumped from the lagoon and dewatered in the centrifuge to an average solids content of 16.7% W.B. The pump flow rate setting was constant for the entire test and the sludge temperature was varied as follows; 86, 79, 73 & 68°C. Residence times were from 5min 49sec to 7min 5sec with the third bank not operating for the run at 68°C. Results indicated that for the treated samples, faecal coliforms and E. coli were not detected at 73°C and above. Salmonella was detected in all samples except that treated to 86°C.

8.4.2 Second Test Run - 26/6/90

The second test run was similar to the first but the sludge temperature was taken to a lower level viz., 86, 79, 73, 68, & 64°C. The average sludge solids content for this test was 17.5 % . Residence times varied from 6 to just over 7 minutes with the power of the third bank switched off for the runs at 68 and 64°C. Faecal coliforms and E. coli were not detected at 68°C and above. Salmonella was detected in all samples except that treated to 86°C, similar to the first test run.

8.4.3 Third Test Run - 24/10/90

The plant was operational for 3.5 hours for this run, with the sludge temperature kept at 86°C for the first 3 hours and the temperature was then dropped to 79°C for the last sample taken. Sludge was drawn from the digestion tank at the STP and dewatered to an average moisture of 21% solids content. The sludge from the digestion tank had an inlet temperature of 32°C at the outlet of the centrifuge which was appreciably higher than for the previous tests (typically 15 to 16°C from the lagoon). The flow rate was also higher than previous tests which resulted in residence times between 4 to 5 minutes. Sampling was conducted every half hour.

It was expected this test run would produce results indicating pasteurisation with exception of possibly the last sample. This was not the case and all samples showed positive or high counts of indicating species. Faecal coliform counts were high so specific tests for E. coli was not undertaken. The likely explanation for these results was that the residence times were too short for effective pasteurisation. Comparison of earlier tests showed residence times of 86°C of at least 5min 49sec had been used for successful pasteurisation.

8.4.4 Fourth Test Run - 7/11/90

This test run used similar temperature parameters to the third test run. However attempts were made to obtain a sludge flow rate low enough to maintain a residence time of at least 6 minutes. Sludge used for this test run was dewatered sludge from the digestion tank with a measured solids content of 22.5%. Testing was conducted over a period of 2.5 hours with sampling conducted every half hour.

The sludge flow rate was monitored closely during this test run. It was noticed that the flow rate had appreciably increased between taking samples 1 & 2. This was because slightly wetter sludge was supplied from the centrifuge. The sludge pump rate was correspondingly reduced marginally between taking samples 2 & 3. Monitoring of the sludge flow rate was undertaken every 5 minutes after this problem. This revealed the sludge flow rate continued to increase slowly due to the supply of marginally wetter sludge. In fact a flow rate of 812kg/hr was measured, (corresponds to a residence time of 5min 15sec) for the period between sampling 3 & 4. The sludge pump rate was again decreased prior to taking sample 4.

The above problem is mentioned because the results revealed complete zero counts on all species except for a faecal coliform count of 600orgs/g for sample 4. The explanation for this result is thought to be as follows. Prior to taking sample 4, the flow rate had increased and resulted in a residence time too short for effective pasteurisation. Although the flow rate was decreased prior to taking sample 4, insufficient time had elapsed for the non pasteurised sludge to be flushed out of the system. Hence a faecal coliform count of 600orgs/g was registered. This is a substantial reduction although not sufficient for class A pathogen reduction.

Table 8.1 Summary of Results

	Max Temp. (oC)	Residence Time (min sec)	Faecal Coliforms (orgs/g)	E. coli (orgs/g)	Faecal Strep.	Salmonella
First test run - 25/6/90						
1	86	5m 49s	0	0	NP	Neg.
2	79	6m 14s	0	0	NP	Pos.
3	73	6m 17s	0	0	NP	Pos.
4	68	7m 5s	$1x10^3$	$1x10^3$	NP	Pos.
Second test run - 26/6/90						
1	86	6m 4s	0	0	NP	Neg.
2	79	6m 26s	0	0	NP	Pos.
3	73	6m 16s	0	0	NP	Pos.
4	68	7m 21s	0	0	NP	Pos.
5	64	7m 9s	$2x10^3$	$2x10^3$	NP	Pos.
Third test run - 24/10/90						
1	89.5	4m 51s	$4x10^4$	NP	Neg.	Neg.
2	87	4m 51s	$7x10^4$	NP	Neg.	Neg.
3	86.5	4m 45s	$4x10^5$	NP	Pos.	Pos.
4	86	4m 45s	$1x10^4$	NP	Neg.	Neg.
5	86.5	4m 22s	$2x10^4$	NP	Neg.	Neg.
6	86	4m 22s	$3x10^6$	NP	Neg.	Pos.
7	79.6	4m 22s	TNTC.	NP	Pos.	Pos.
Fourth test run - 7/11/90						
1	86	6m 39s*	0	0	Neg.	Neg.
2	86	5m 26s*	0	0	Neg.	Neg.
3	86	6m 39s*	0	0	Neg.	Neg.
4	86	7m 28s*	600	0	Neg.	Neg.
5	86	6m 48s*	0	0	Neg.	Neg.

Pos. - positive

Neg. - negative

NP - not performed

TNTC - too numerous to count.

* - Residence time if flow rate had remained constant. Refer to section 8.4.4.

Table 8.2 First test run - 25/6/90

Run No	1.	2.	3.
Time	1.00pm	1.25pm	1.45pm
Temperature			
Inlet T(°C)	16	16	16
T1/T1set (°C)	40.0/40.0	39.6/40.0	40.7/40
T2/T2set (°C)	49.8/50.0	50.2/50.0	50.0/50.0
T3/T3set (°C)	75.0/75.0	70.3/70.0	65.1/65
T3 actual (°C)	86	79	73
T exit (range)	68 (65-78)	65 (61-72)	61 (57-65)
Microwave Power			
Power zone 1 (kW)	18	17	18
Power zone 2 (kW)	12	12	13
Power zone 3 (kW)	11	7.8	3.6
Total power (kW)	41	36.8	34.6
Flow rate (kg/hr)	732	684	678
Residence Time	5m 49s	6m 14s	6m 17s
Effectiveness (%)	146	137	130
Treated Samples	1	2	3
Faecal Coliforms	0	0	0
E. Coli	0	0	0
Faecal Streptococci	NP	NP	NP
Salmonella	Negative	Positive	Positive

Table 8.2 First test run - 25/6/90
(ctd...)

Run No	4.			
Time	2.10 pm			
Temperature				
Inlet T(°C)	16			
T1/T1set (°C)	39.9/40.0			
T2/T2set (°C)	54.1/50.0			
T3/T3set (°C)	61.9/60.0			
T3 actual (°C)	68			
T exit (range)	58 (58-59)			
Microwave Power				
Power bank 1 (kW)	18			
Power bank 2 (kW)	13			
Power bank 3 (kW)	0			
Total power (kW)	31			
Flow rate (kg/hr)	684			
Residence Time	7m 5s			
Effectiveness (%)	134			
Treated Samples	4			
Faecal Coliforms	$1x10^3$			
E. Coli	$1x10^3$			
Faecal Streptococci	NP			
Salmonella	Positive			
Additional Samples	Initial A	Initial B	Comp. (fine)	Comp. (course)
Faecal Coliforms	Confluent	$2x10^4$	Confluent	Confluent
E. Coli	$1x10^4$	NP	NP	NP
Faecal Streptococci	NP	NP	NP	NP
Salmonella	Positive	Positive	Positive	Positive

Comments
- Machine shut down several times in morning because of no sludge supplied from centrifuge.
- Average sludge solids content for test 16.7% wet basis.
- Sludge coming from digestor.
- NP: not performed.
- Confluent: no result.
- "Initial" sample refers to sludge sample taken at the exit of the centrifuge.
- "Comp". refers to composted sludge/sawdust mix (1 of fine and 1 of coarse particles).

Table 8.3 Second test run - 26/6/90

Run No	1.	2.	3.
Time	11.15am	11.40am	12.15pm
Temperature			
Inlet T (°C)	15	15	15
T1/T1set (°C)	39.9/40.0	40.0/40.0	39.9/40.0
T2/T2set (°C)	55.5/55.0	51.8/51.0	49.3/49.0
T3/T3set (°C)	75.7/75.0	70.1/70.0	64.9/65.0
T3 actual (°C)	86	79	73
T exit (range)	73 (63-85)	71 (60-80)	69 (60-75)
Microwave Power			
Power bank 1 (kW)	18	17	17
Power bank 2 (kW)	18	13	11
Power bank 3 (kW)	5.1	2.5	4.8
Total power (kW)	41.1	32.5	32.8
Flow rate (kg/hr)	702	662	679
Residence Time	6m 4s	6m 26s	6m 16s
Effectiveness (%)	141	152	140
Treated Samples	1	2	3
Faecal Coliforms	0	0	0
E. Coli	0	0	0
Faecal Streptococci	NP	NP	NP
Salmonella	Negative	Positive	Positive

Table 8.3 Second test run - 26/6/90
(ctd...)

Run No	4.	5.
Time	1.00pm	1.20pm
Temperature		
Inlet T (°C)	15	15
T1/T1set (°C)	39.7/40.0	39.8/40.0
T2/T2set (°C)	50.2/50.0	46.7/46.5
T3/T3set (°C)	60.7/60.0	56.1/55.0
T3 actual (°C)	68	64
T exit (range)	62 (60-65)	54 (45-58)
Microwave Power		
Power bank 1 (kW)	17	17
Power bank 2 (kW)	13	8.8
Power bank 3 (kW)	0	0
Total power (kW)	30	25.8
Flow rate (kg/hr)	660	679
Residence Time	7m 21	7m 9s
Effectiveness (%)	136	150
Treated samples	4	5
Faecal Coliforms	0	$2x10^3$
E. Coli	0	$2x10^3$
Faecal Streptococci	NP	NP
Salmonella	Positive	Positive

Additional Samples	Initial A	Initial B	Comp. A	Comp. B	Sawdust
Faecal Coliforms	$2x10^3$	$2x10^3$	$2x10^3$	Confluent	Confluent
E. Coli	$2x10^2$	$2x10^2$	$2x10^2$	NP	NP
Faecal Streptococci	NP	NP	NP	NP	NP
Salmonella	Positive	Positive	Positive	Positive	Positive

Comments
- Average sludge solids content for test 17.5% wet basis.
- Sludge coming from lagoon.
- Confluent: no result.
- NP: not performed.
- "Initial" sample refers to sludge sample taken at the exit of the centrifuge.
- "Comp" refers to composted sludge/sawdust mix.
- "Sawdust" refers to sawdust/sludge mixture.

Table 8.4 Third test run - 24/10/90

Run No	1.	2.	3.	4.
Time	11.00am	11.30am	12.00pm	12.30pm
Temperature				
Inlet T (oC)	32	32	32	32
T1/T1set (oC)	44.5/45.0	45.5/45.0	44.9/45.0	44.9/45.0
T2/T2set (oC)	56.3/60.0	59.8/60.0	59.8/60.0	59.8/60.0
T3/T3set (oC)	76.5/75.0	75.4/75.0	75.3/75.0	74.7/75.0
T3 actual (oC)	89.5	87.4	86.5	86.0
T exit (range)	75 (90-73)	73 (80-67)	71 (67-77)	71 (78-66)
Microwave Power				
Power bank 1 (kW)	16	15	13	14
Power bank 2 (kW)	20	20	19	20
Power bank 3 (kW)	12	6	6	7
Total power (kW)	48	41	38	41
Flow rate (kg/hr)	878	878	896	896
Residence Time	4m 51s	4m 51s	4m 45s	4m 45s
Effectiveness (%)	125	138	165	138
Treated Samples	1	2	3	4
Faecal Coliforms	$4x10^4$	$7x10^4$	$4x10^5$	$1x10^4$
E. Coli	NP	NP	NP	NP
Faecal Streptococci	Negative	Negative	Positive	Negative
Salmonella	Negative	Negative	Positive	Negative

Table 8.4 Third test run - 24/10/90
ctd...

Run No	5.	6.	7.	
Time	1.00pm	1.30pm	2.00pm	
Temperature				
Inlet T (°C)	32	32	32	
T1/T1set (°C)	44.9/45.0	44.8/45.0	41.1/40.0	
T2/T2set (°C)	57.3/60.0	57.3/60.0	55.1/55.0	
T3/T3set (°C)	75.5/75.0	74.5/75.0	70.5/70.0	
T3 actual (°C)	86.5	86.0	79.6	
T exit (range)	66 (60-72)	62 (60-68)	61 (58-66)	
Microwave Power				
Power bank 1 (kW)	17	16	10	
Power bank 2 (kW)	20	20	18	
Power bank 3 (kW)	11	11	9	
Total power (kW)	48	47	37	
Flow rate (kg/hr)	976	976	976	
Residence Time	4m 22s	4m 22s	4m 22s	
Effectiveness (%)	129	131	146	
Treated Samples	5	6	7	
Faecal Coliforms	$2x10^4$	$3x10^6$	TNTC	
E. Coli	NP	NP	NP	
Faecal Streptococci	Negative	Negative	Positive	
Salmonella	Negative	Positive	Positive	
Additional Samples	Initial A	Initial B	Mixed C	Mixed D
Faecal Coliforms	$3x10^5$	$2x10^5$	TNTC	TNTC
E. Coli	NP	NP	NP	NP
Faecal Streptococci	Positive	Positive	Negative	Negative
Salmonella	Positive	Positive	Positive	Positive

Comments
- E. Coli testing was not performed because of a high faecal coliform count.
- Sludge coming directly from digestor.
- Bank 3 one magnetron down.
- Run 7 temperature reduced to 70°C.
- NP: not performed.
- TNTC: to numerous to count.
- "Initial" sample refers to sludge sample taken at the exit of the centrifuge.
- "Mixed" samples refer to sludge mixed with sawdust after microwaving.

Table 8.5 Fourth test run - 7/11/90

Run No	1.	2.	3.	4.
Time	11.30am	12.00pm	12.30pm	1.00pm
Temperature				
Inlet T (°C)	32	32	32	32
T1/T1set (°C)	45.9/45.0	45.2/45.0	45.7/45.0	45.5/45.0
T2/T2set (°C)	60.0/60.0	60.0/60.0	60.1/55.0	60.1/60.0
T3/T3set (°C)	75.3/75.0	75.2/75.0	74.8/75.0	74.8/75.0
T3 actual (°C)	86	86	86	86
T exit (range)	68 (66-71)	68 (66-71)	67 (65-73)	68 (65-72)
Microwave Power				
Power bank 1 (kW)	7.9	7.7	7.5	6.7
Power bank 2 (kW)	13	16	13	12
Power bank 3 (kW)	7.2	7.1	5.7	6.2
Total power (kW)	27.8	30.8	26.2	24.9
Flow rate (kg/hr)	640	782	641	570
Residence Time	6m 39s	5m 26s	6m 39s	7m 28s
Effectiveness (%)	145	160	154	144
Treated Samples	1	2	3	4
Faecal Coliforms	0	0	0	600
E. Coli	0	0	0	0
Faecal Streptococci	Negative	Negative	Negative	Negative
Salmonella	Negative	Negative	Negative	Negative

Table 8.5 Fourth test run - 7/11/90
(ctd...)

Run No	5.			
Time	1.30pm			
Temperature				
Inlet T (°C)	32			
T1/T1set (°C)	45.0/45.0			
T2/T2set (°C)	59.9/60.0			
T3/T3set (°C)	74.9/75.0			
T3 actual (°C)	86			
T exit (range)	66 (64-68)			
Microwave Power				
Power bank 1 (kW)	7.0			
Power bank 2 (kW)	12			
Power bank 3 (kW)	6.3			
Total power (kW)	25.3			
Flow rate (kg/hr)	627			
Residence Time	6m 48s			
Effectiveness (%)	156			
Treated Samples	5.			
Faecal Coliforms	0			
E. Coli	0			
Faecal Streptococci	Negative			
Salmonella	Negative			
Additional Samples	Initial A	Initial B	Mixed C	Mixed D
Faecal Coliforms	$6x10^3$	$8x10^3$	20	100
E. Coli	$6x10^3$	$8x10^3$	20	100
Faecal Streptococci	Positive	Positive	Negative	Negative
Salmonella	Positive	Positive	Positive	Positive

Comments
- Average solids content 22.5%.
- Flow rate turned down after run 2.
- Sludge coming directly from digestor.
- Dial setting on pump was reduced after run 2 and run 3 because measured flow rate was slowly increasing.
- Bank 3 one magnetron down.
- "Initial" sample refers to sludge sample taken at the exit of the centrifuge.
- "Mixed" samples refer to sludge mixed with sawdust after microwaving.

8.5 Discussion of Results

8.5.1 Microbiological Analysis

Analysis of untreated sludge samples revealed consistently high contamination of faecal coliforms and E. coli. Salmonella and faecal streptococci tests all produced positive results. Hence all the untreated sludge was heavy contaminated with pathogens, as expected.

Results of treated sludge samples have been plotted in Figures 8.3 to 8.7. Figure 8.3 is a plot of sludge temperature versus residence time indicating zero or non-zero counts. The positive count for faecal coliforms in the fourth test run is the only result which does not correspond to the trend of the plot. Because of the earlier explanation (Section 8.4.4), this point should be considered erroneous or relocated with a residence time of 5 to 6 minutes. If this is the case, results indicate sludge temperatures of greater than 73°C with residence times of at least 6 minutes should produce zero faecal coliform counts. For a temperature of 68°C, results indicate a residence time of at least 7min 21sec is required for zero counts.

Figure 8.4 is plot of E. coli results indicating zero or non zero counts. This plot is identical to Figure 8.3, except that the point considered erroneous in Figure 8.3 recorded a zero count and does not disturb the trend of the plot. Hence, the conclusion for this plot is similar to above. Hence, sludge temperatures of greater than 73°C with residence times of at least 6 minutes should produce zero E. coli counts. For a temperature of 68°C, results indicate a residence time of at least 7min 21sec is required for zero counts.

Figure 8.5 is a plot indicating negative or positive faecal streptococci results. Analysis of this indicator species was not possible for the first and second test run and hence results for this species are minimal. However results show that for a negative result, residence times should be at least 5min 26sec for a sludge temperature of 86°C.

Figure 8.6 is a plot indicating negative or positive salmonella results. Results show that for a negative result, residence times should be at least 5min 26sec for a treatment temperature of 86°C or above.

Figure 8.7 is a plot indicating class A pathogen reduction (or pasteurisation). Ignoring the erroneous test point, class A pathogen reduction was achieved for a treatment temperature of at least 86°C and a residence time of at least 5min 26sec. However, because of the erroneous result, it would be appropriate to consider a residence time of at least 6 minutes for effective pasteurisation.

Samples taken of the sludge and sawdust mixture and from the stockpile show at least some type of contamination. This was expected because of the environment of the surroundings and there being no provisions for accommodating cold sludge pumped through the microwave unit during start-up. In particular during start-up, cold sludge was pumped through the unit and then microwave energy is applied. The plant then takes approximately one-half hour to reach and stabilise in temperature. During this period, untreated sludge contaminated the mixing hopper, conveyor and the stockpile. Hence untreated sludge hence contaminates the mixing hopper, conveyor and the stockpile. Furthermore once the system does reach temperature, the treated sludge is open for recontamination as soon as it enters the mixing hopper.

Figure 8.3 Faecal coiform results

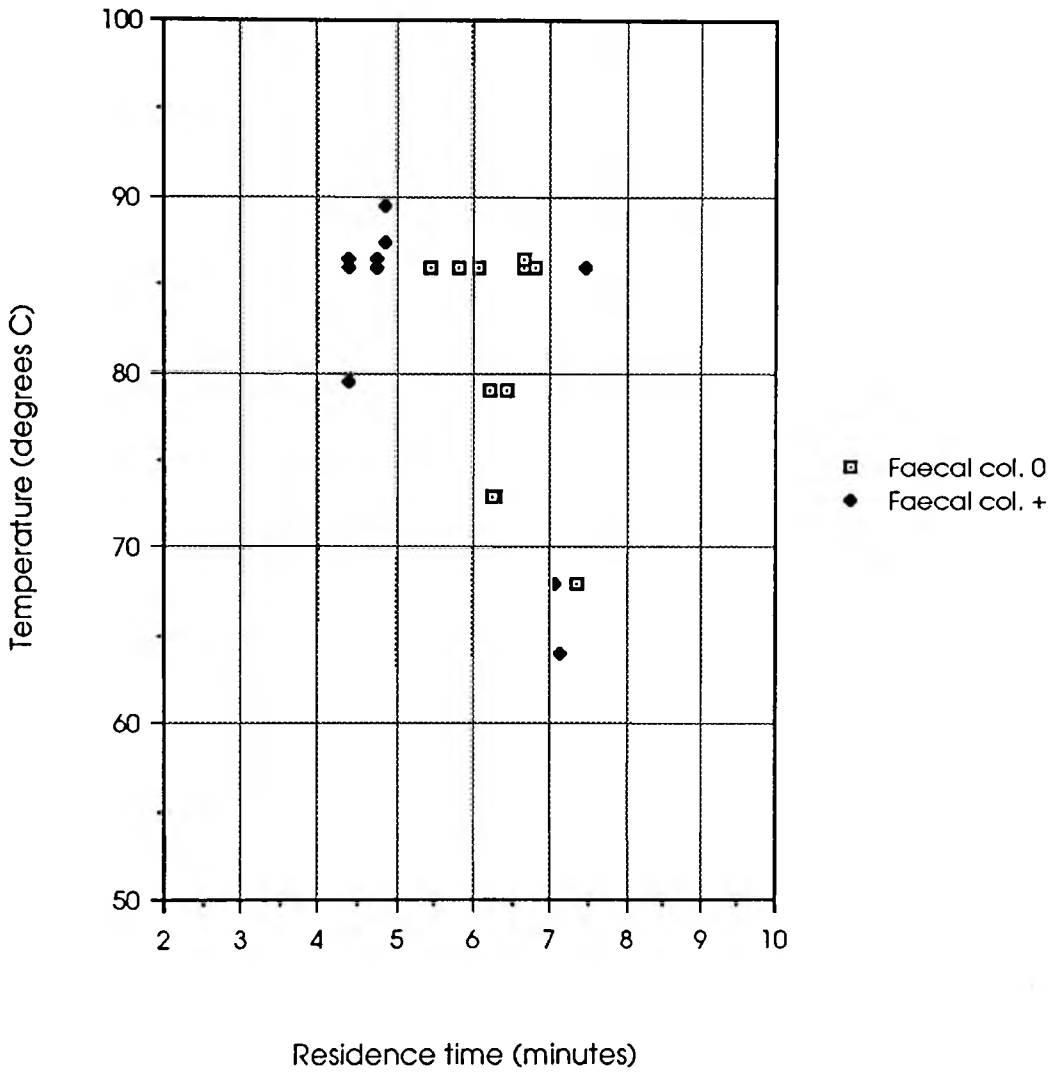


Figure 8.4 E. coli results

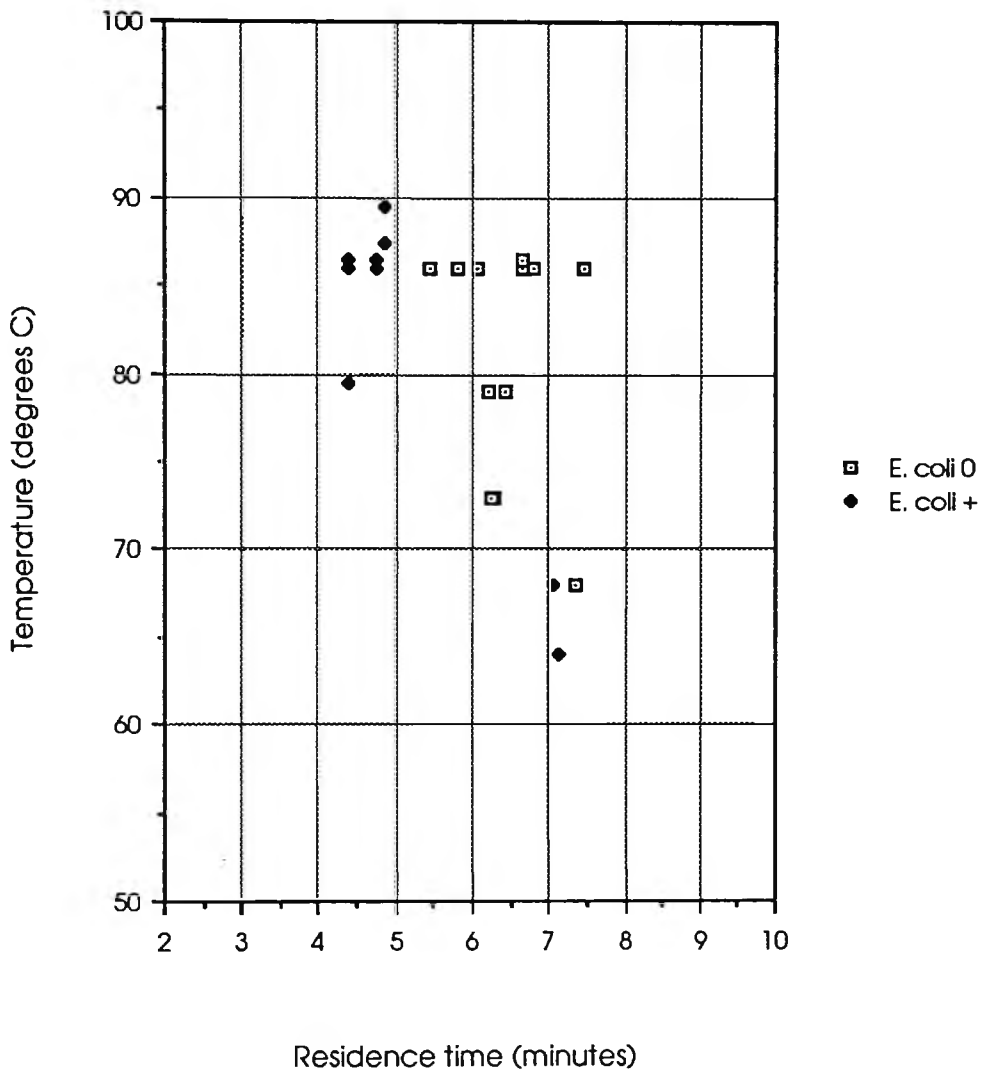


Figure 8.5 Faecal streptoccoci results

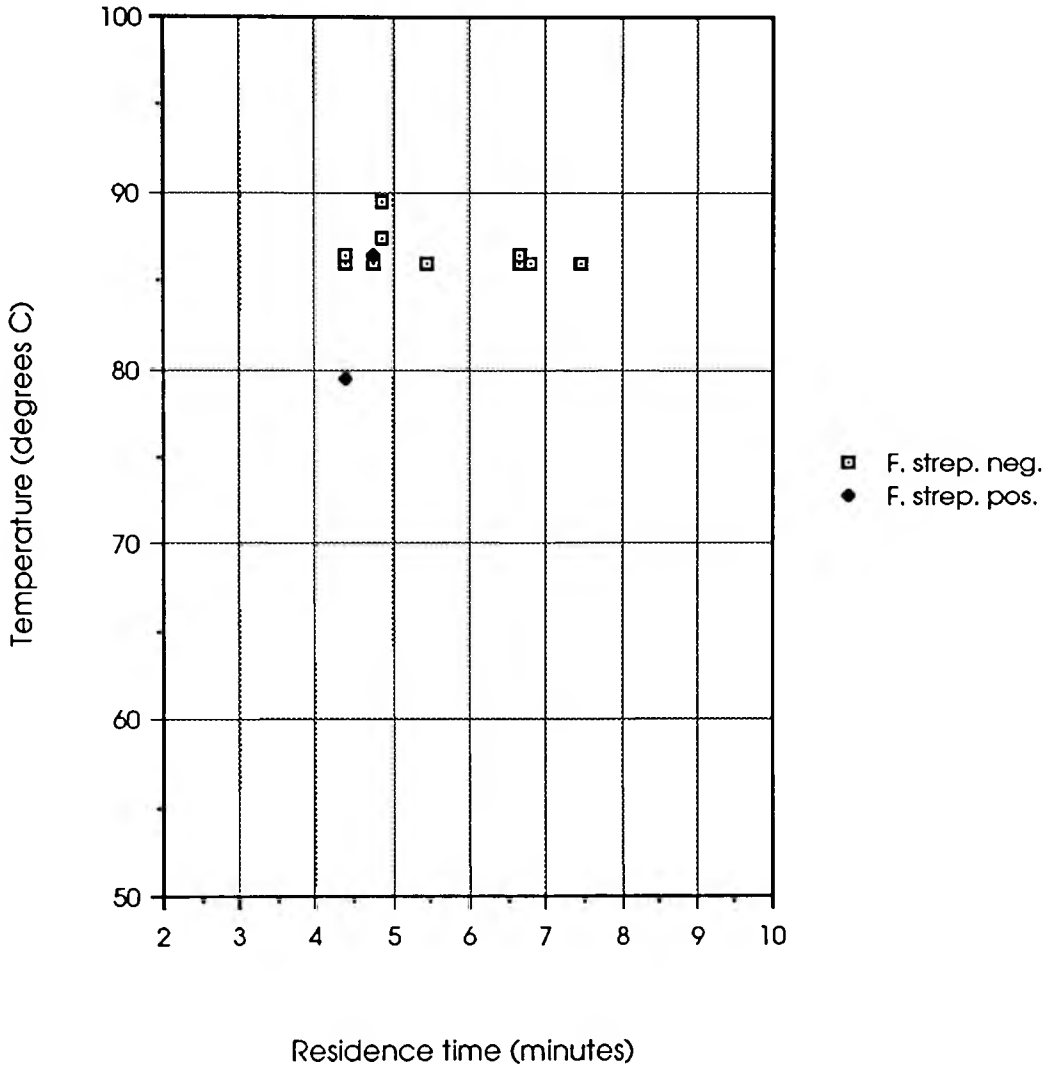


Figure 8.6 Salmonella results

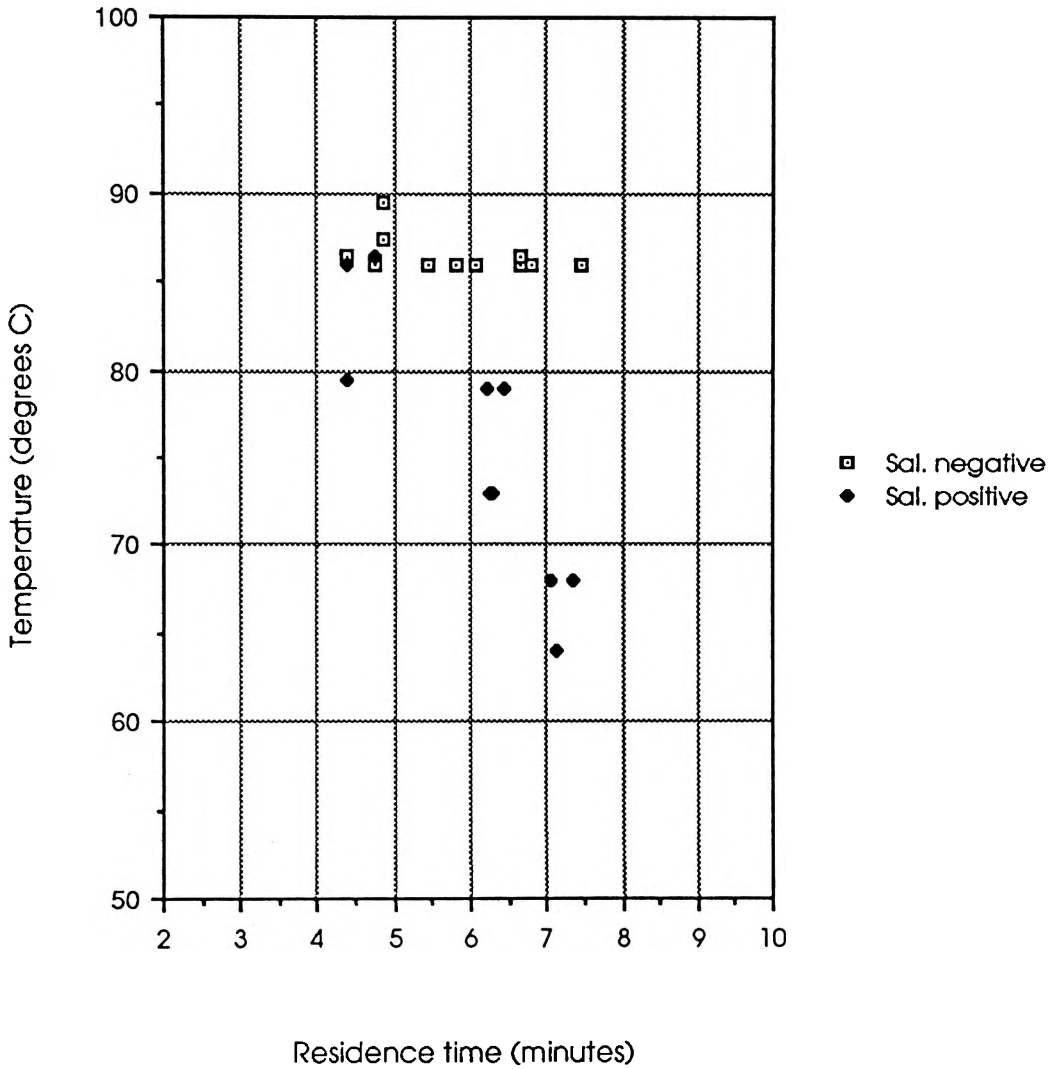
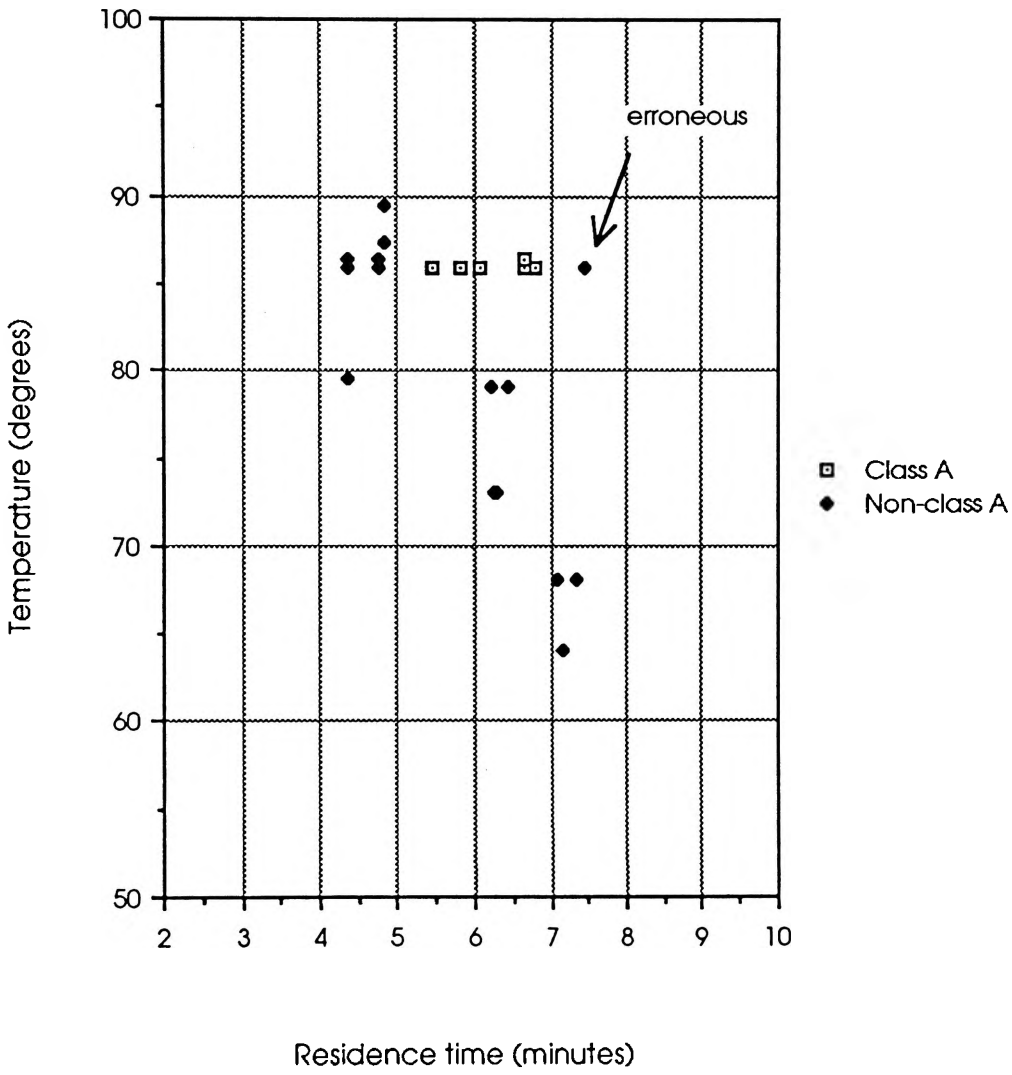


Figure 8.7 Class A pathogen reduction results



8.5.2. Microwave Effectiveness

An overall view of the variation of the microwave effectiveness versus sludge temperature and microwave effectiveness versus sludge flow rate are presented in Figure 8.8 and 8.9. Both plots depict scattered results and it is difficult to identify any trends. The observed microwave effectiveness ranged from 125% to 165% with an average of 143%. The explanation for these high values is considered to be a combination of several factors outlined below.

Firstly, the sludge temperature or bulk temperature could be lower than actually measured. This is because when determining the actual sludge temperature, a thermocouple was inserted into the sludge pipe at the end of the third bank. This protruded into the 75mm diameter sludge pipe approximately 20mm. Hence the probe was measuring the sludge temperature midway between the edge and centre of the sludge. Although the microwave energy heated the sludge from both sides of the pipe a temperature gradient from the outside to the inside of the sludge was still noticed. This could have resulted in an indicated bulk temperature somewhat higher than actual.

Secondly, as shown in Table 6.1 the specific heat of sludge is lower than that of water at high solids content. However when calculating the microwave effectiveness the assumption was made that the specific heat was equal to that of water. This assumption obviously results in higher predicted values for the effectiveness.

Thirdly, the microwave power level for the plant was measured and indicated by a digital readout on the control panel. This readout was calibrated to display 5kW maximum power output to the magnetron. However it is possible with this type of

Figure 8.8 Microwave effectiveness vs temperature

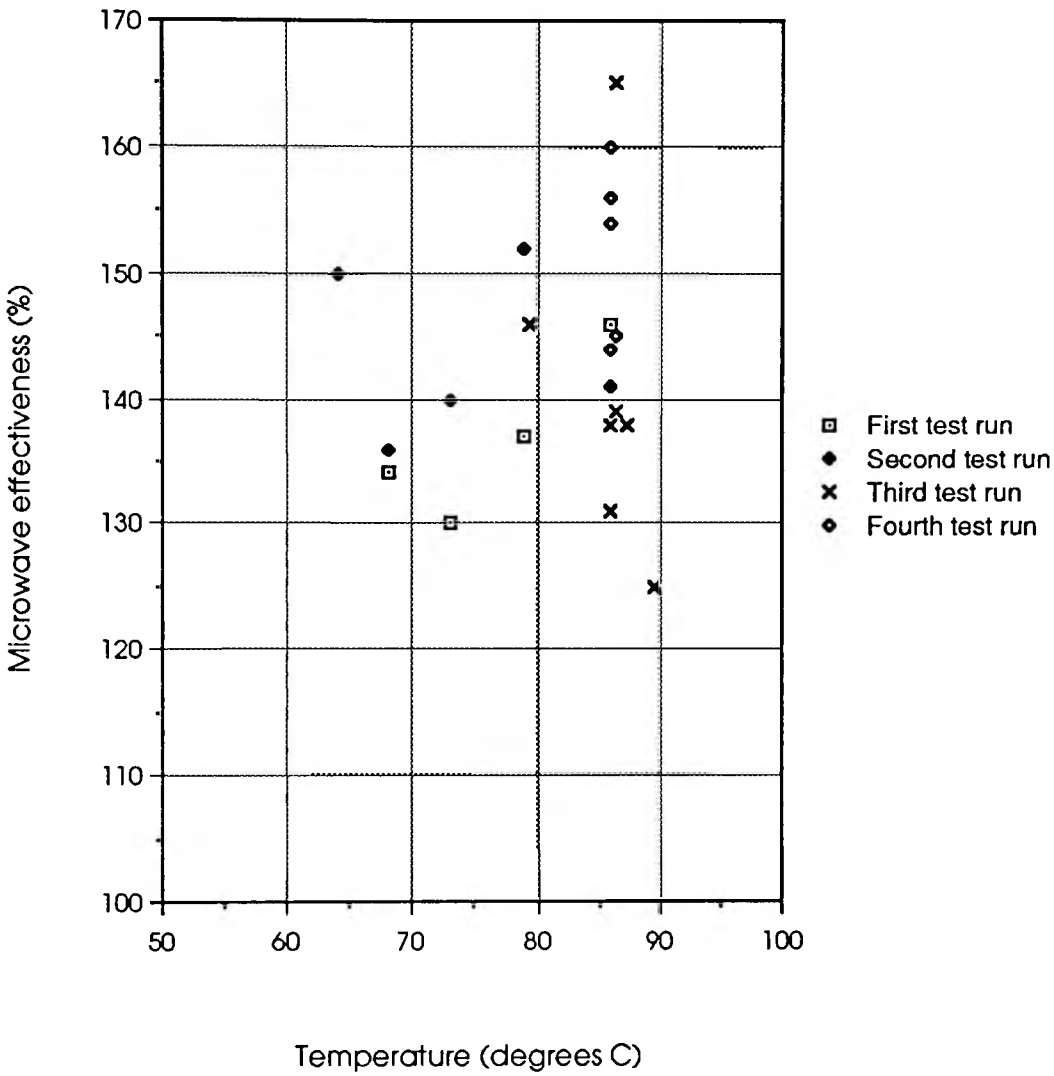
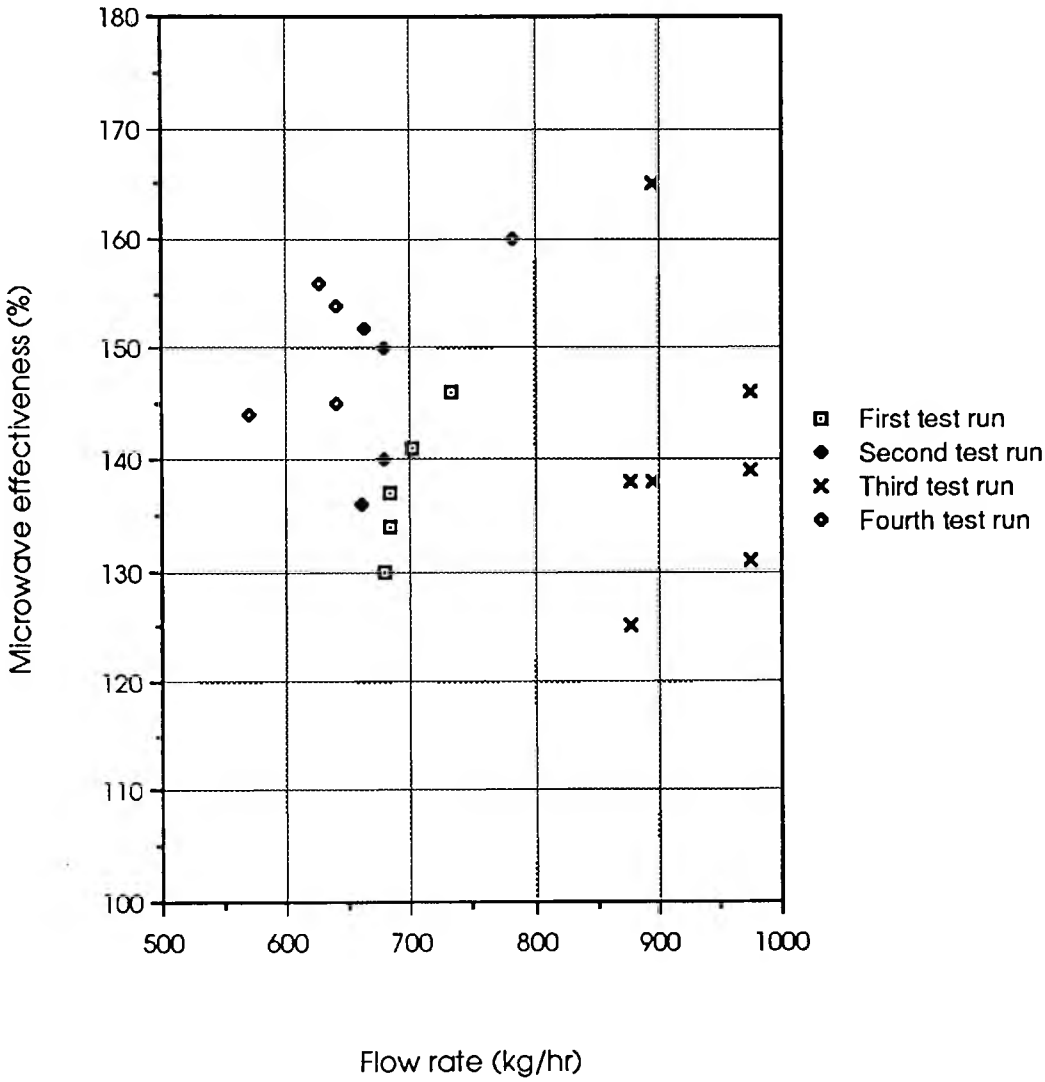


Figure 8.9 Microwave effectiveness vs flow rate



magnetron to output up to a maximum of 6kW of microwave power.[28] Hence the power readout meter could be reading lower than actual.

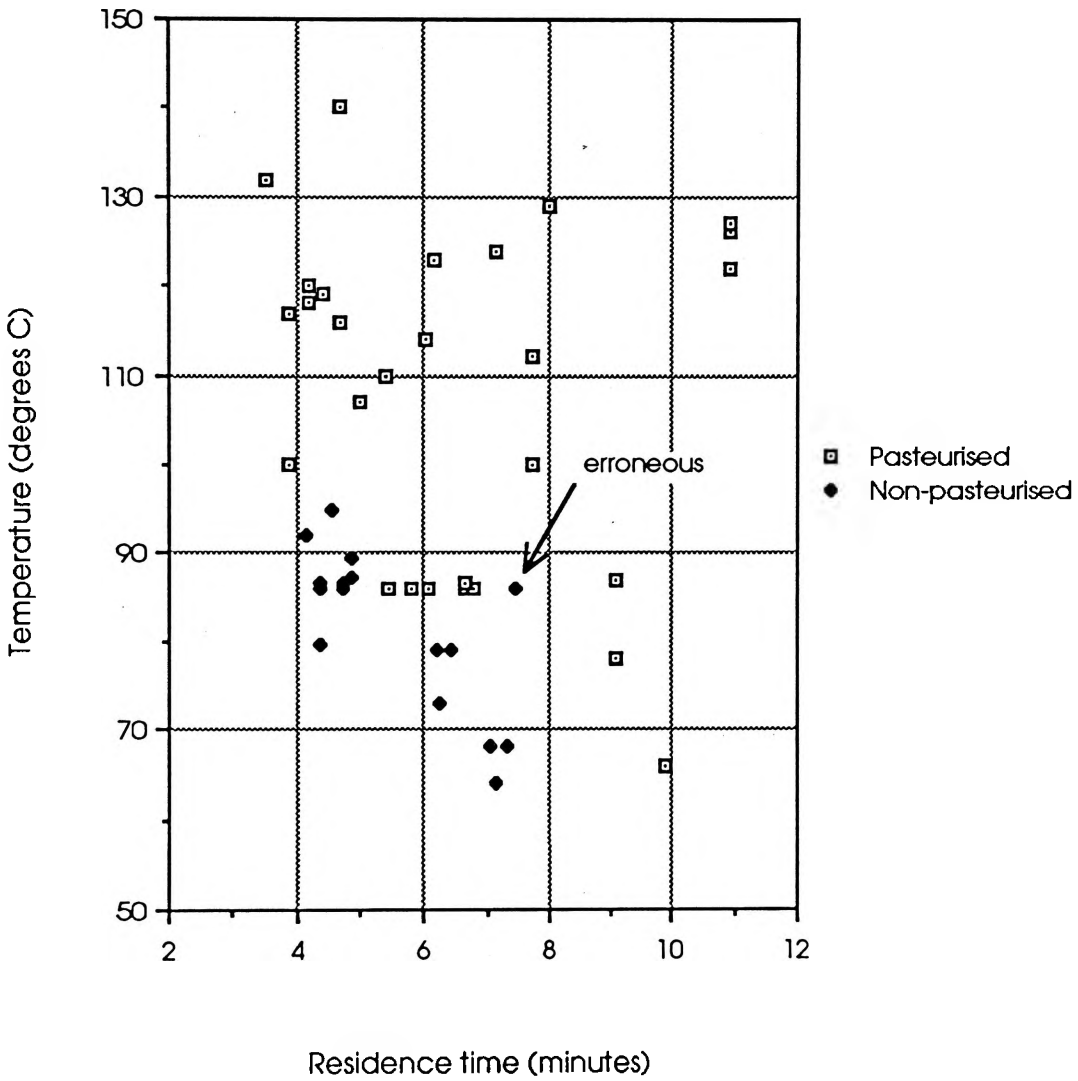
8.5.3 Comparison of Results and Suggested Improvements

The 60kW microwave pasteurising plant at Shellharbour was effective in producing class A pathogen reduced sewage sludge, although the plant in its tested condition would need modification to fully utilise its available capacity. It was shown that class A pathogen reduction was achieved, for a treatment temperature of at least 86°C and a residence time of at least 6 minutes. This corresponds to an outside pipe temperature of 75°C and a flow rate of not more than 710kg/hr. This proposed level for class A pathogen reduction is a minimum requirement and the proposed operating zone should have a margin for safety, such as a longer residence time.

A comparison of results from the 60kW plant with the results for the 40kW plant is shown in Figure 8.10. It is an composite of Figure 7.3 and 8.7. An examination of the plot shows that results correlate well allowing identification of the boundaries for effective pasteurisation.

With the 60kW plant's proposed setting of 86°C and 6 minutes, the microwave unit needs an increased length of residence pipe to enable the full 60kW of power to be utilised. Presently, the unit cannot operate more than a flow rate of 710kg/hr without the residence time dropping below 6 minutes. Considering 60kW of power is available and an initial sludge temperature of 32°C, a flow rate of approximately 1350kg/hr of wet sludge is possible. At this flow rate the residence time of the sludge would be too short for effective pathogen reduction (1350kg/hr corresponds to a residence time of only 3 minutes).

Figure 8.10 Comparison of 40 & 60kW pasteurisation results



Presently, the residence pipe is 16.2 metres long. However if it was doubled in length, then at a maximum flow rate of 1350kg/hr, the residence time would correspond to 6min 9sec. Hence, for any flow rate settings less than maximum, the sludge would have longer residence times and an appropriate margin for effective pathogen reduction. Furthermore, this longer residence pipe should enable lower treatment temperatures to be adopted. Results from Figure 8.10 indicate this is feasible.

Problems may occur when the residence pipe is increased in length. This is because the added back pressure, due to the greater pumping distance on the down stream side of the microwave unit may be excessive for the teflon liners in the pipe heaters . If this problem occurs the sludge flow rate may have to be monitored continually to ensure the maximum flow rate is not exceeded. This modification however will not fully utilise the available microwave power and reduce the maximum throughput of the plant.

The problem of start-up of the unit needs attention to prevent recontamination of the sludge on the downstream side after exiting the residence pipe. The sludge processed during start up should be separated at the discharge of the residence pipe with only properly treated sludge proceeding to any further mixing or stockpiling.

8.5.4 Maximum Throughput and Scale-up

The theoretical maximum throughput of the plant can be determined. Assuming an appropriate pasteurising temperature for sludge of 86°C and considering an average microwave effectiveness of 143%.

This high value of the microwave effectiveness would seem initially to be incorrect and a more appropriate value of approximately 70% should be used. However the value of 143% is correct if assuming the sludge has specific heat constant of water (Section 8.5.2). A microwave effectiveness of 70% would correspond to a specific heat constant of approximately half of that of water (Section 6.1). Both sets of values will yield approximately the same maximum throughput.

Two cases are considered, initial sludge temperatures of 15°C and 32°C, respectively. Rearranging equation 4.18a then,

$$\dot{m} = \frac{\eta_s P}{C_p \Delta T} \qquad ...(8.1)$$

where:

$\dot{m}$ = mass flow rate

η = 1.43

P = 60kW

C_p = 4.184 kJ/kg °C

ΔT = 86 - T_I °C

Case 1 - 15°C initial temperature,

$$\dot{m} = \frac{1.43 \times 60}{4.184 \times (86 - 15)} \times 60^2$$

= 1040 kg/hr of wet sludge

= 229 kg/hr dry sludge (based on a solids content of 22%).

Case 2 - 32°C initial temperature,

$$\dot{m} = \frac{1.43 \times 60}{4.184 \times (86 - 32)} \times 60^2$$

= 1367 kg/hr of wet sludge

= 300 kg/hr dry sludge (based on a solids content of 22%).

When scaling this plant direct linear extrapolation is applied. Hence equation 8.1 is used for theoretical scaling of the plant to any desired capacity.

8.6 Economic Analysis

To conduct an economic analysis the total input power to the plant must be known. Unfortunately determination of the total power was not possible although an accurate estimate can be calculated . For instance, neglecting the sludge pump power at this stage, nearly all the power supplied to the plant is used by the magnetrons which have an efficiency of up to 72%. Other equipment such as high voltage transformers, cooling fans, water pump, cooling tower consume a small amount of power as compared to the magnetrons. On accounting for this additional load the overall electrical to microwave energy transfer efficiency of 60% can be assumed.

The sludge pumps power consumption was 30kW at full capacity. However the pumps flow rate capacity was far in excess of the 60kW plants capacity to process sludge to pasteurisation and hence did not draw full power during testing. Hence assume that the sludge pump power consumption was 40% of maximum (ie 12kW) with the pasteurisation plant operating at full power.

Based on the above assumptions the total plant input power can then be calculated. This is the power required to pasteurise sludge at the plants maximum theoretical capacity of 1350kg/hr wet sludge or 300kg/hr dry sludge (refer to section Section 8.5.4).

$$\text{Input Power} = \frac{60\text{kW}}{0.6} + 12$$

$$= 112\text{kW}$$

On assuming an electricity cost of $0.12/kWhr, the electricity cost per tonne of pasteurised sludge can be estimated. Two cases are considered, cost per tonne of wet sludge and cost per tonne of dry sludge, respectively.

$$\text{Cost/tonne} = \frac{\text{Input power x Electricity cost}}{\text{mass flow rate}} \qquad ...(8.2)$$

Case 1 - Wet sludge

$$\text{Cost/tonne} = \frac{112\text{kW x \$0.12}}{1.35\text{tonnes/hr}}$$

$$= \$10 \text{ per tonne of wet sludge}$$

Case 2 - Dry solid tonne (22% solids content)

$$\text{Cost/tonne} = \frac{112\text{kW x \$0.12}}{1.35\text{tonnes/hr x 0.22 solids content}}$$

$$= \$45 \text{ DST}$$

There are two other factors which have to be quantified in the economic analysis. That is the initial capital cost and maintenance cost of the plant. Generally the cost of industrial microwave equipment is $3000 to $5000 per kiloWatt of microwave power. Hence the cost of the 60kW microwave unit at Shellharbour STP is in the vicinity of $240000. The sludge pump can vary greatly in cost depending upon the type, size and amount of automation required. The positive displacement plunger pump used at Shellharbour retails for approximately $180000. However that pump was oversized for the application and is also one of the most expensive pumps available. Cheaper alternatives are possible. In view of this an estimated pump cost of $100000 is expected. The only major individual maintenance cost would be for replacement

magnetrons. These magnetrons have an expected life of 8000 hours and a retail cost of $4000.

To determine the appropriate cost of pasteurisation of sludge per tonne of product several assumptions have been made and outlined below,

- Plant life of 6 years and an full operation 24 hours per day,
- 210 working days per year,
- Ancillary equipment inluding building and site costs to be $260000
- The plant will be operating for 90% of the time. The other 10% will allow for maintenance and breakdowns,
- Value of plant after 6 years is zero.
- Plant operates 3 x 8 hour shifts (ie 24 hour day), with 1 operator required per shift,
- Cost of magnetrons are $4000 each and have an expected life of 8000 hours.
- Allow 5% of the capital cost for general maintenance per annum.
- An inflation rate of 8%.

Capital costs

60kW microwave unit	=	$240000
Pump	=	$100000
Ancillary equipment	=	$260000
Total capital cost of plant	=	$600000

Energy cost per annum

112kW x \$0.10 x 24hrs x 210 days x 0.9 = \$61000 per annum

Maintenance cost per annum

Cost of replacement magnetrons per year,

$$\frac{12 \times \$4000 \times 24\text{hrs} \times 210\text{ days} \times 0.9}{8000\text{hrs}} = \$27200 \text{ per annum}$$

Cost of general maintenance,

\$400000 x 0.05 = \$20000 per annum

Total maintenance cost = \$47200 per annum

Labour cost per annum

Assume an average cost per operator of \$40000 per annum therefore,

\$40000 x 3 operators = \$120000 per annum

Depreciation

Value of plant after 6 years is zero. Therefore total depreciation for the 6 year period is \$600000 or \$10000 per annum.

Total cost of plant for 6 years of operation

Capital cost			$600000
Energy	$61000 @ 8% inflation	=	$448000
Maintenance	$47200 @ 8% inflation	=	$346000
Labour	$120000 @ 8% inflation	=	$880000
Depreciation		=	$600000
Total cost of plant			$2874000

Sludge processing quantity per annum

0.3 DST/hr x 24hrs x 210 x 0.9 = 1361 DST per annum

Overall cost of processing sludge per tonne

Therefore the overall cost of processing sludge to pasteurisation is,

$$\frac{\$2874000}{1361 \text{ DST} \times 6 \text{ years}} = \$352 \text{ per DST}$$

or assuming a sludge solids content of 22%,

$352 x 0.22 = $77 per tonne of wet sludge

8.7 Suggestions for Further Work

The following are suggestions which can be pursued to improve the efficiency and operations of the current plant.

- Increase the residence pipe length to fully utilise the available power and then investigate reducing the processing temperature.
- The use of heat recovery equipment to increase efficiency and capacity of the plant.
- Improvement of the materials handling equipment on the downstream side of the processing plant with the aim of preventing recontamination.
- Investigate the microwave penetration depth and specific heat constant of sewage sludge at varying solids content.
- Improvement of the sludge temperature monitoring instrumentation to obtain a true indication of the sludge bulk temperature.
- Upgrading the plant to enable automatic operation of all equipment from one remote location.
- Further full economic evaluation of any modifications.
- The use of ceramics or any other materials as a liner material for the microwave cavity instead of teflon.
- The effectiveness and economic comparison of the use of other forms of energy to effect pasteurisation of sewage sludge.

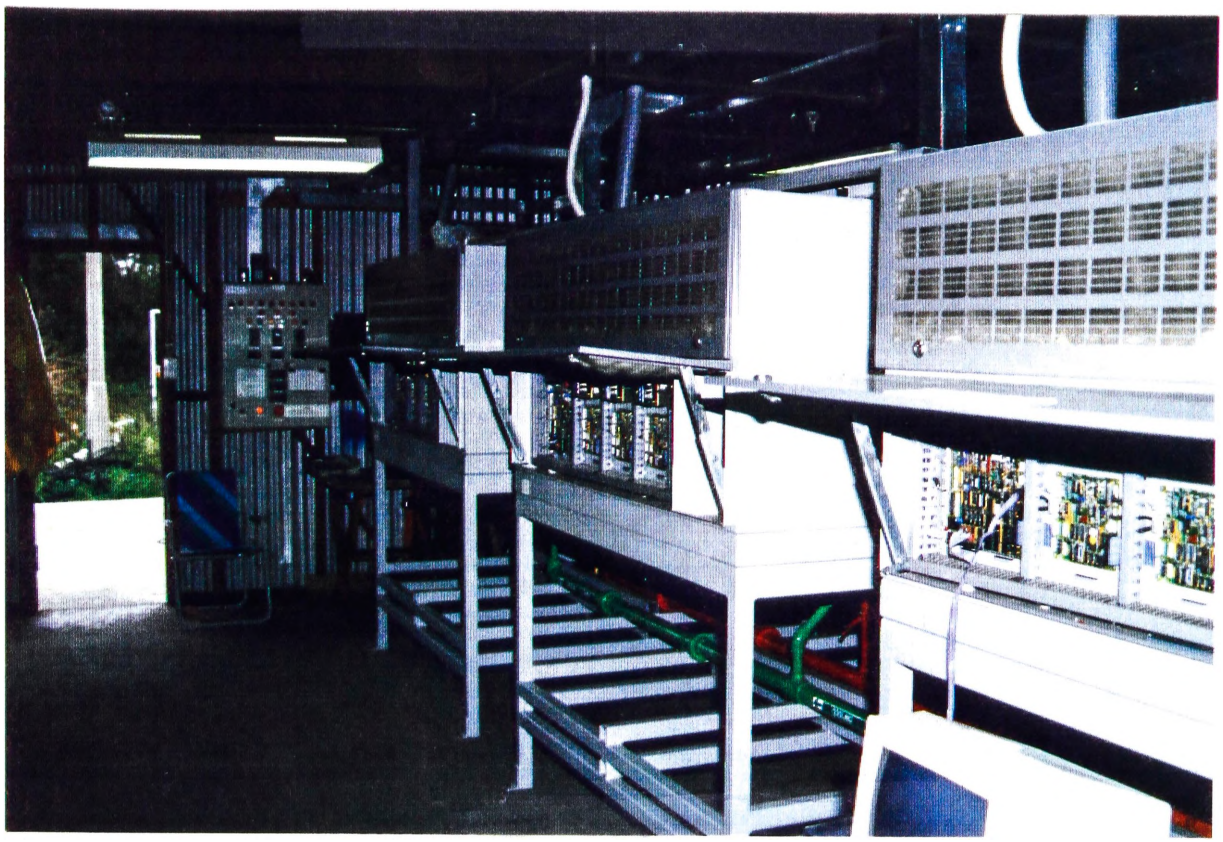


Photo 8.1 Three banks of the 60kW microwave power supply

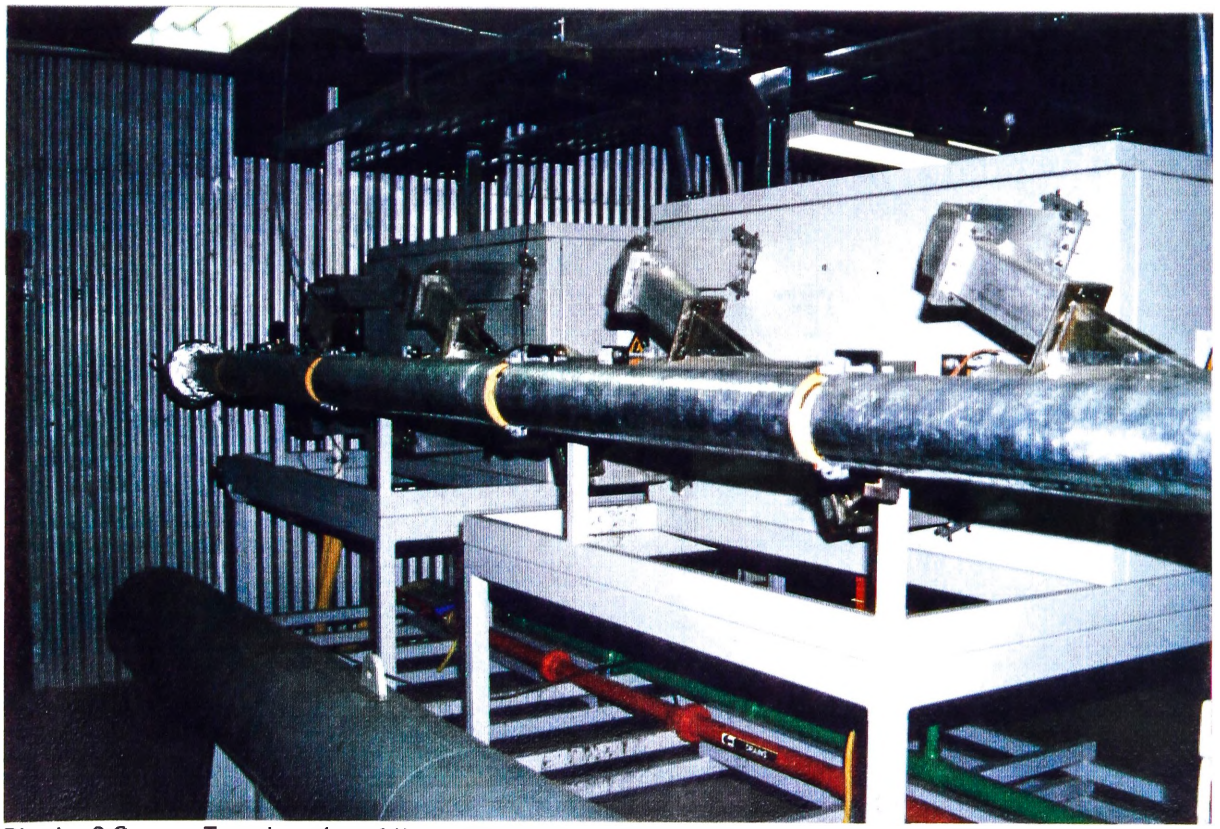


Photo 8.2 Two banks of the microwave pipe heaters and part of the insulated residence pipe.

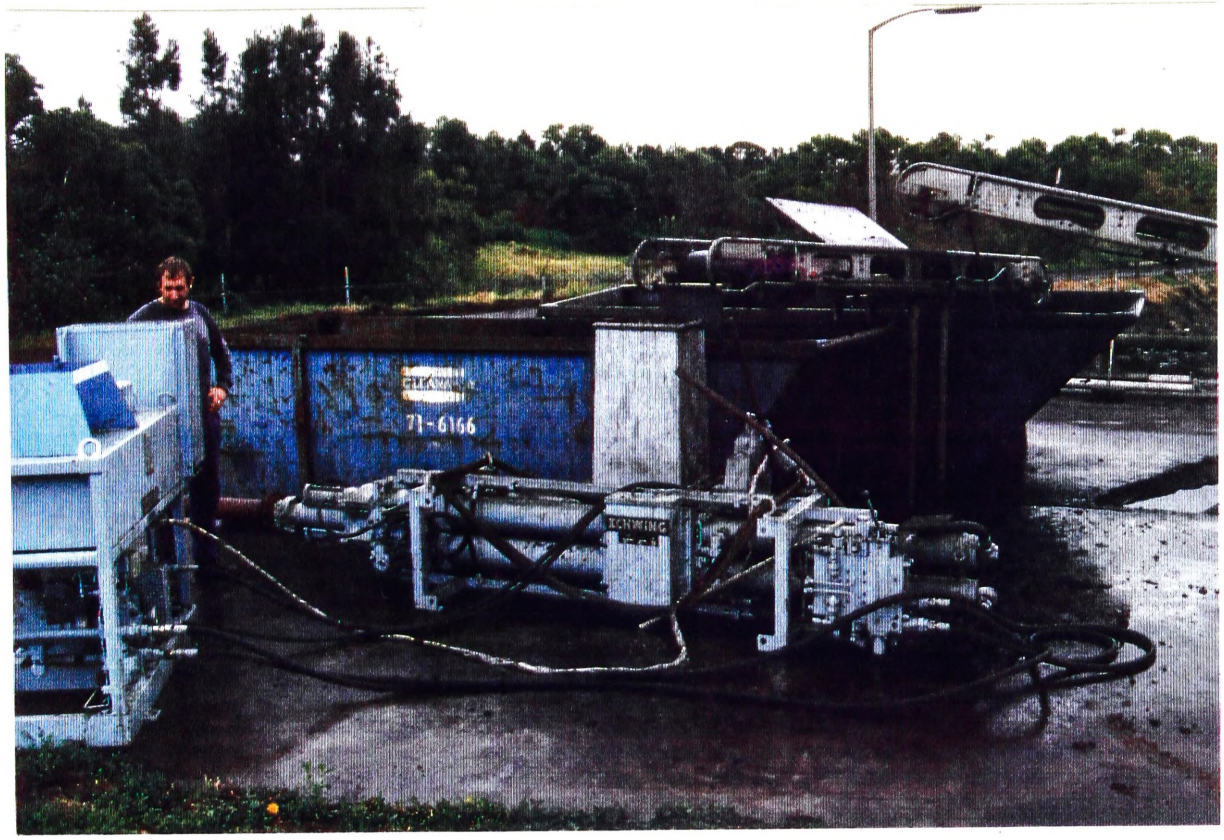


Photo 8.3 The positive displacement plunger pump.

Photo 8.4 The inlet pipe line, discharge residence pipe and sawdust storage and mixing hopper.

9. Conclusion

9. Conclusion

The 40kW microwave sludge processing plant successfully demonstrated the treatment of sewage sludge on a continuous basis. The design and construction of the plant was conducted at MARC's Coniston laboratory and testing of sewage sludge was conducted at Shellharbour STP. It used the unique heating characteristics of microwaves to selectively heat the sludge only, by the use of special microwave applicators called pipe heaters. A dual peristaltic pump enabled sludge to be processed up to a temperature of 130°C and to a required level of sterilisation.

The dual peristaltic pump proved to be very effective and an elegant solution to the problem of heating the sludge over 100°C. The unit greatly simplified the mechanical operation of the process. A simple heat exchanger across the hot and cold sludge pipe enabled some heat recuperation. The heat exchanger also acted as an effective temperature limiting device to preserve the discharge peristaltic pump from possible damage due to excessive temperature.

Initial commissioning test runs of the plant on water showed the design was most suitable and effective for heating liquids above 100°C. A microwave efficiency of 74% was recorded for the pipe heater using tap water.

The experimental 40kW plant proved sludge could be treated to levels of pasteurisation or sterilisation continuously. Parameters used to determine the process effectiveness were maximum temperature attained by the sludge and the residence time of the sludge at this temperature. Various combinations of parameters were found to produce the desired effect.

Results indicated pasteurisation of sludge was achieved at sludge temperatures varying from 66°C for at least 10 minutes residence time to 95°C for at least 5 minutes residence time (Figure 8.10). Sterilisation was achieved for treatment temperature of 125°C and a residence time of at least 10 minutes. However, parameters of 132°C for 3 min 32 sec also produced sterilised sludge.

An investigation of the effectiveness of this 40kW plant resulted in an average microwave effectiveness of 66% based on the specific heat of water. The inclusion of the heat exchanger increased the microwave effectiveness by an average of 5%. The average plant effectiveness was found to be 46%.

Successful results from the experimental 40kW sludge processing plant resulted in the development of a dedicated 60kW microwave sludge pasteurisation plant, which was also subsequently installed at Shellharbour STP.

Tests conducted on this 60kW plant proved that it was effective in pasteurising sewage sludge. Results indicated class A pathogen reduction (or pasteurisation) was achieved for a treatment temperature of 86°C and a residence time of at least 6 minutes. These results were found to be directly comparable with results obtained from the 40kW experimental plant (Figure 8.10).

However, the plant in its present condition required modification to fully utilise its available capacity. The length of the residence pipe was insufficient to fully utilise the total 60kW of microwave power while attaining a residence time of at least 6 minutes. Calculations indicate the residence pipe should be twice as long.

Results also indicated that a maximum throughput of the 60kW plant was 1350kg/hr of wet sludge or 300 kg/hr of dry sludge (at 22% solids content). This would make the 60kW plant's capacity ideally suited to many of the inland STP's located in the Sydney, Blue Mountains and Illawarra areas. The power consumed by the plant at the maximum throughput rate was estimated to be 112kW. The typical expected electricity cost is $10 per tonne of wet sludge or $45 per DST.

An economic evaluation of the plant was undertaken assuming a capital cost of $600000, a 24 hour day and a 6 year life span of the plant. Calculations revealed an indicated cost of processing sludge to pasteurisation of $77 per tonne of wet sludge or $352 per DST. Further work should be undertaken to improve the existing plant and incorporate heat recovery which would greatly reduce processing costs.

The successful development work on microwave processing of sewage sludge has not only established a process to pasteurise or sterilise sewage sludge but also developed a process that can heat any liquids or sludges passing through a pipe using microwave energy. Temperatures exceeding 100°C are easily obtainable and temperatures of several hundred degrees are possible by using ceramics as the linear material in the microwave cavity.

10. References

10. References

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11. Appendices

11.1 Appendix A - Specifications for Philips Magnetron YJ1600

(Extract taken from Philips Technical Publication 219.[26])

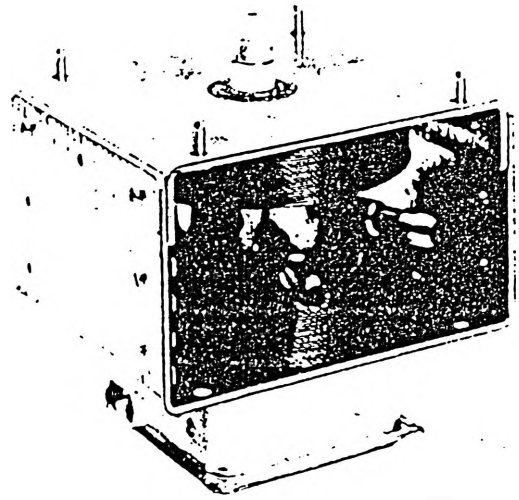
YJ1600 magnetron for microwave heating up to 6 kW

The YJ1600 is a fixed-frequency continuous-wave magnetron for microwave heating. It sets a new standard for compactness, efficiency and installation ease. The output power can be continuously adjusted from 0,5 kW to 5 kW.* For higher powers, two or more tubes can operate from one high-voltage supply. Control and stabilization of the output power are straightforward. The YJ1600 uses permanent magnet and electromagnet field generation to enhance operating flexibility and to reduce the total cost of microwave generators.

The main features of the YJ1600 are:

- low-voltage/low-power stabilization and regulation by using an electromagnet which cuts control circuit complexity and cost, and simplifies the high-voltage supply
- instant response to variation of the electromagnet field permits instant adaptation to process requirement variations, hence optimal energy use and improved product quality
- can be operated without a circulator up to 5 kW output power (in the sink region) provided v.s.w.r. $\leqslant 4$
- no stray magnetic field
- no constraints on mounting position
- high basic efficiency
- integrated cathode filter prevents spurious radiation
- can be coupled directly into the waveguide.

* output powers up to 6 kW are possible; ask for details.



The YJ1600 is a continuous-wave magnetron for microwave heating up to 6 kW. It has an efficiency of up to 72%. In addition, the combination of permanent magnet and electromagnet field generation with instant response to changes in the latter ensures optimum energy use. It is compact (158 mm x 150 mm x 120 mm) for its output power, produces no stray magnetic field and there are no constraints on mounting position

TABLE I

Quick reference data on the YJ1600; v.s.w.r. = 2,5 in the sink phase

		output power		
		0,5 to 5 kW	6 kW	
frequency, fixed within the range	f	2,45 to 2,47	2,45 to 2,47	GHz
output power control and stabilization		by electromagnet	by electromagnet	
anode voltage, peak	V_{ap}	7,2	7,2	kV
anode current	I_a	100-950	1150	mA
filament voltage:				
during warm-up	V_f	5	5	V
during operation	V_f	0-4	0	V
filament current during warm-up	I_f	33	33	A
efficiency		72%	72%	
maximum v.s.w.r.		4	*	
cooling (typ.):				
anode block		2 ℓ/m water	2 ℓ/m water	
r.f. filter box		120 ℓ/m air	120 ℓ/m air	
antenna		60 ℓ/m air	60 ℓ/m air	
mounting position		any	any	
mass (typ.)		4,3	4,3	kg

* For 6 kW output power, the tube must only be operated with a v.s.w.r. of about 2,5 in the sink phase, see main text.

11.2 Appendix B - Fluid Flow Loss Coefficient for Philips Magnetron YJ1600

Aim: To determine the fluid flow loss coefficient for Philips YJ1600 magnetron.

Theory: Using equation 4.19 and rearranging in terms of the loss coefficient K.

$$K = \frac{2 h_f g}{U^2}$$

where,

$$U = \frac{Q}{A}$$

Diameter of piping = 12.5mm

$$= \frac{Q}{\frac{\pi}{4} 0.0125^2}$$

$$= 8149 Q$$

Substituting U into above equation,

$$K = \frac{2 \times 9.81 \times h_f}{(8149 Q)^2}$$

$$= \frac{0.295 \times 10^{-6} h_f}{Q^2}$$

Reynolds number must be determined to check for turbulent flow, therefore, from equation 4.20,

$$R_e = \frac{U D \rho}{\mu}$$

$\rho = 1000 kg/m^3$

$\mu = 1 \times 10^{-3}$

$$= \frac{U 0.0125 \times 1000}{1 \times 10^{-3}}$$

$$= 12500 U$$

Method: Mains pressure tap water was connected in line to one YJ1600 magnetron. A manometer measured the pressure drop across the magnetron and the flow rate was measured by timing the required time to fill a container of known volume. Results are shown in Table B.1

Results:

Table B.1 Results of YJ1600 loss coefficient experiment

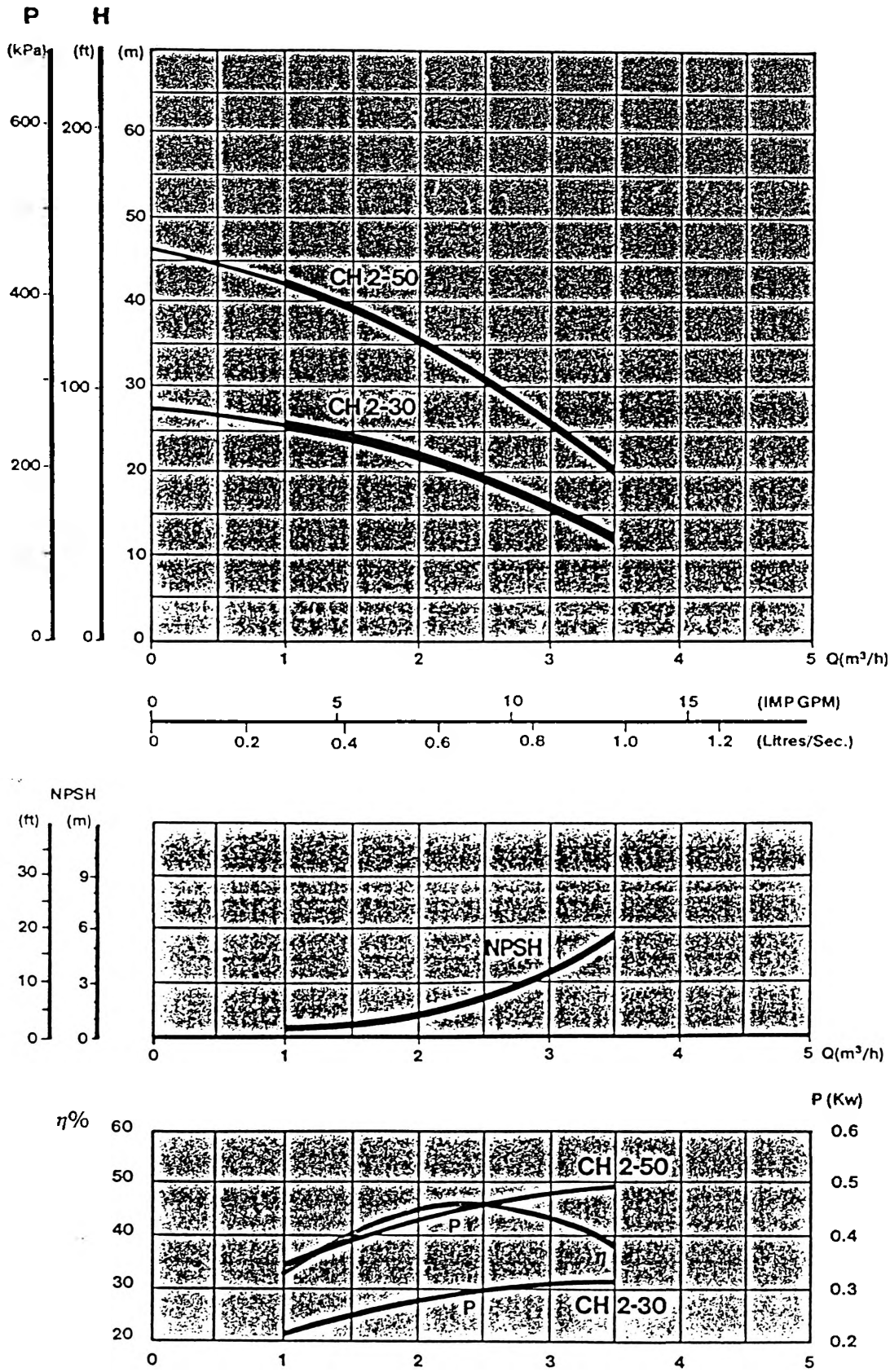
Flow rate (L/min)	Head loss (m)	Velocity (m/sec)	Loss Coefficient	Reynolds Number
1.22	0.61	0.166	435.2	2075
1.87	0.97	0.254	294.6	3175
2.88	1.09	0.391	139.6	4888
3.10	1.03	0.421	113.8	5263
3.48	1.18	0.473	103.5	5913
3.85	1.32	0.523	94.6	6538
3.96	1.60	0.538	108.4	6725
4.09	1.52	0.555	96.5	6938
4.46	1.74	0.606	92.9	7575
4.94	2.05	0.671	89.2	8388
5.14	2.31	0.698	92.9	8725
5.35	2.50	0.727	92.8	9088
6.02	3.06	0.818	89.7	10225
6.42	3.41	0.872	87.9	10900
6.76	3.86	0.922	88.9	11525

Consider the flow rates in excess of 3L/min since strong linearity is shown at these higher flow rates. Furthermore the magnetrons do not typically operate below 3L/min. At flow rates in excess of 3L/min the Reynolds number indicates turbulent flow. Considering the average loss coefficient after flow rates above 3L/min, then,

$$K = 96$$

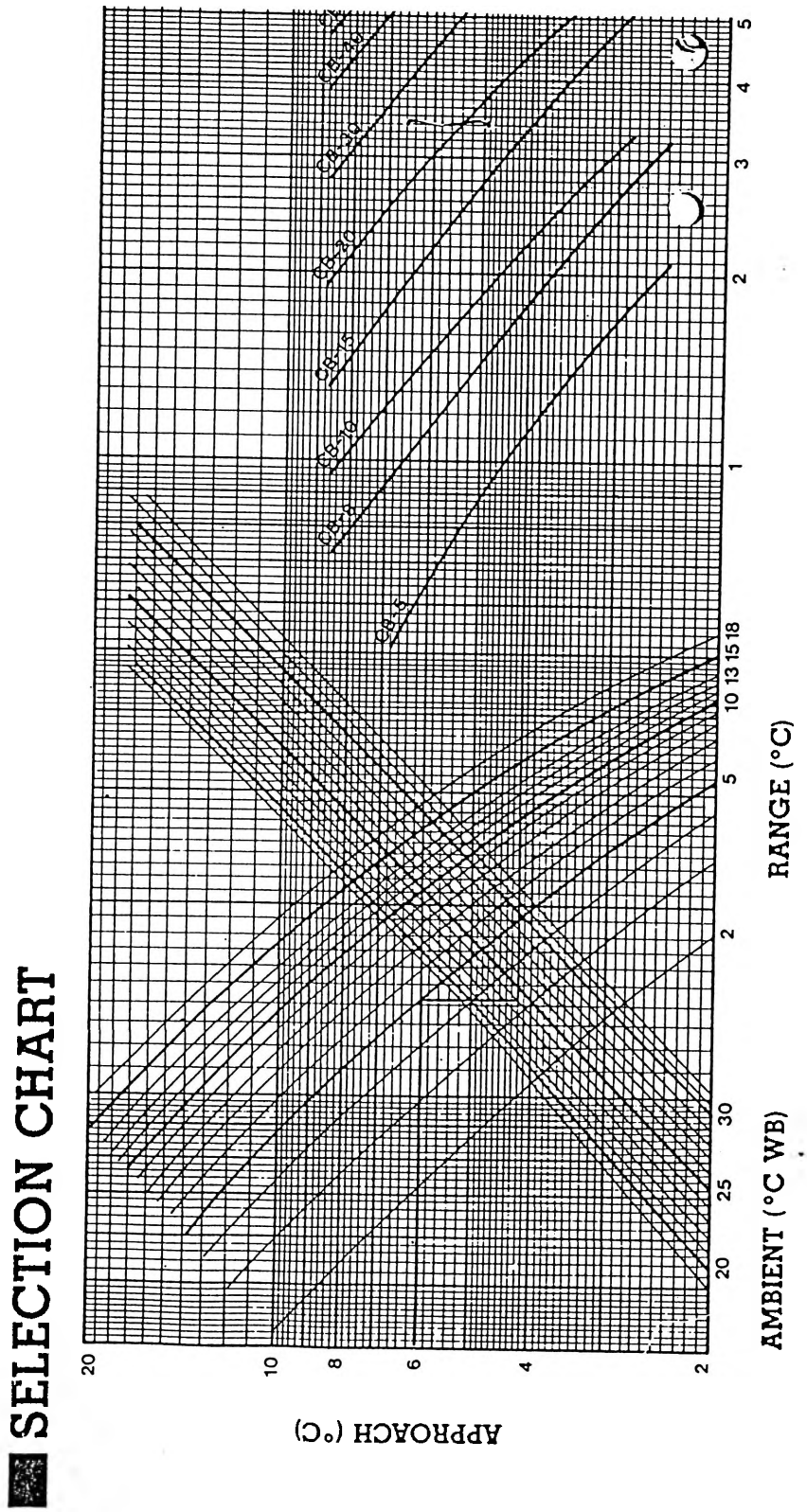
11.5 Appendix C - Pump Performance Chart

(Extract taken from Grundfos CH General Transfer Pump Performance Data.)



11.6 Appendix D - Cooling Tower Design Chart

(Extract from Coolboy Cooling Tower Specification and Design brochure.)



11.7 Appendix E - Analysis Reports for 40kW Plant

FORDHAM LABORATORIES PTY. LTD.

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24th April, 1989

Mr. J Bacchus
Water Board
P O Box 17
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REPORT OF ANALYSIS

NO: 89 - 548

Samples : Sludge
Lab. Nos. : 2093 - 2100
Date : 13. 4.89
Method : Salmonella sp. AS 1766 with Rappaport enrichment
Faecal Coliforms: MPN to EC Broth at 44.5°C
E. coli AS 1766

RESULTS

	Total Plate Count orgs/g	Faecal Coliforms MPN	E. coli MPN	Salmonella sp.
Sludge Samples -				
6	7.7×10^3	ND/g	ND/g	ND/50g
10	1.9×10^4	ND/g	ND/g	ND/50g
12	4.1×10^3	ND/g	ND/g	ND/50g
16	4.4×10^3	ND/g	ND/g	ND/50g
2 Initial Hopper Sample		≥2400/g	≥2400/g	ND/50g
4 . 12/4		ND/0.1g	ND/0.1g	ND/50g
8 Initial Sample		920/g	920/g	ND/50g
14 Initial Sample		350/g	350/g	ND/50g

ND = not detected under the conditions of test used on this occasion
≥ = greater than or equal to

ANALYSED BY: Annette Fordham

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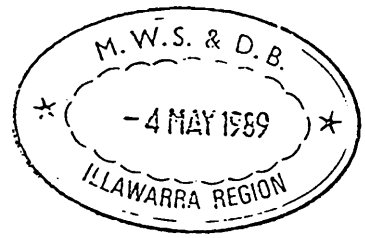

REPORT OF ANALYSIS

NO: 89 - 594

Samples : Sludge
Lab. Nos. : 2383 - 2387
Date : 26. 4.89
Method : Salmonella sp. AS 1766 with Rappaport enrichment
Faecal Coliforms: MPN to EC Broth at 44.5°C
E. coli AS 1766

RESULTS

	Total Plate Count orgs/g	Faecal Coliforms MPN	E. coli MPN	Salmonella sp.
Initial Sample 1.	4.1×10^8	≥2400/g	≥2400/g	present/50g
2pm Sample 2. Exit Temp.	2.5×10^1	ND/g	ND/g	ND/50g
3. Hot	0.5×10^1	ND/g	ND/g	ND/50g
4. Hot	<10	ND/g	ND/g	ND/50g
5. Hot	0.5×10^1	ND/g	ND/g	ND/50g

ND = not detected under the conditions of test used on this occasion
≥ = greater than or equal to
< = less than

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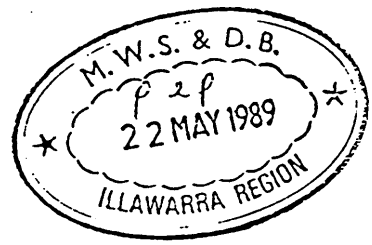
18th May, 1989



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REPORT OF ANALYSIS

NO: 89 - 708

Samples	:	Sludges
Lab. Nos.	:	2878 - 2896
Date	:	11. 5.89
Method	:	Salmonella sp. AS 1766 with Rappaport enrichment Faecal Coliforms: MPN to EC Broth at 44.5°C E. coli AS 1766 Total Plate Count 30°C/3 days

RESULTS

	Total Plate Count orgs/g	Faecal Coliforms MPN	E. coli MPN	Salmonella sp. /25g
Initial Sample 10 May	1.7×10^8	≥2400/g	≥2400/g	present
1139 Bacteria Count Sample A-1 4.5.89 Pump 50 T4 111 T5 106	$>10^7$	ND/g	ND/g	ND
Sample A-1 10 May Pump 30 T5 102 12.27am	2.8×10^3	ND/g	ND/g	ND
11.42 Bacteria Count Sample A-2 4.5.89	1.4×10^8	ND/0.1g	ND/0.1g	ND
Sample A-2 May 10 Pump 35 T5 103	4.6×10^3	ND/g	ND/g	ND
Sample A-3 May 10 Pump 40 T5 98-100	1.9×10^5	ND/g	ND/g	ND
Sample A-4 May 10 Pump 45 T5 91-93	4.4×10^5	ND/g	ND/g	ND
Sample A-5 May 10 Pump 50 T5 90	4.6×10^5	ND/g	ND/g	ND
Sample A-6 May 10 Pump 55 T5 73°	9.3×10^5	46/g	24/g	ND
Sample A-7 May 10 Pump 60 T5 72	1.0×10^6	≥240/g	≥240/g	ND

.....2

Fordham Laboratories 18th May 1989

Report No. 89 - 708 cont.

	Total Plate Count orgs/g	Faecal Coliforms MPN	E. coli MPN	Salmonella sp. /25g
Sample B-1 May 10 Pump 30 T6 96 12.27am	3.4×10^5	≥240/g	≥240/g	ND
Bacteria Count Sample B-1 4.5.89 Pump 55 T4 1112 T5 103 12.07	$>10^7$	ND/g	ND/g	ND
Sample B-2 May 10 Pump 35 T6 95°	$>10^6$	4.3/g	4.3/g	ND
Bacteria Count Sample B-2 4.5.89 12.09	5.5×10^8	ND/0.1g	ND/0.1g	ND
Sample B-3 May 10 Pump 40 T6 87	$>10^6$	ND/g	ND/g	ND
Sample B-4 May 10 Pump 45 T6 81-83	2.5×10^7	≥240/g	≥240/g	ND
Sample B-5 May 10 Pump 50 T6 82	6.1×10^5	≥240/g	≥240/g	ND
Sample B-6 May 10 Pump 55 T6 58	$>10^6$	≥240/g	≥240/g	ND
Sample B-7 May 10 Pump 60 T6 60	1.1×10^7	≥240/g	≥240/g	ND

≥ = greater than
> = greater than or equal to
ND = not detected under the conditions of test used on this occasion

ANALYSED BY: Annette Fordham

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30th May, 1989

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PO Box 17
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REPORT OF ANALYSIS

NO: 89 - 789

Samples	:	Sludges
Lab. Nos.	:	3032 - 3047
Date	:	17. 5.89
Method	:	Salmonella sp. AS 1766 with Rappaport enrichment Faecal Coliforms: MPN to EC Broth at 44.5°C E. coli AS 1766 Total Plate Count 30°C/3 days

RESULTS

	Total Plate Count orgs/g	Faecal Coliforms MPN	E. coli MPN	Salmonella sp. /25g
Initial Sample 1 16.5.89	2.8×10^8	$\geq 2.4 \times 10^3$ orgs/g	$\geq 2.4 \times 10^3$ orgs/g	present
Initial Sample 2 16.5.89	2.2×10^8	$\geq 2.4 \times 10^3$ orgs/g	$\geq 2.4 \times 10^3$ orgs/g	present
B6 T=62°C	6.4×10^5	1.1×10^3 orgs/g	1.1×10^3 orgs/g	ND
B5 T=68°C	4.0×10^5	4.0×10^0 orgs/g	4.0×10^0 orgs/g	ND
A6 T=74°C	2.1×10^6	ND/0.1g	ND/0.1g	ND
B4 T=75°C	3.4×10^5	ND/0.1g	ND/0.1g	ND
B3 T=79°C	1.8×10^5	9.0×10^0 orgs/g	9.0×10^0 orgs/g	ND
A5 T=80°C	6.1×10^5	ND/0.1g	ND/0.1g	ND
A4 T=84°C	4.7×10^5	ND/0.1g	ND/0.1g	ND
B1 T=99°C	2.5×10^3	ND/g	ND/g	ND
A2 T=101°C	0.5×10^1	ND/g	ND/g	ND

.....2

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	Total Plate Count orgs/g	Faecal Coliforms MPN	E. coli MPN	Salmonella sp. /25g
A1 T=103°C	2.0×10^1	ND/g	ND/g	ND
A1 T5 100-105°C 11.5.89	1.0×10^1	ND/g	ND/g	ND
B1 T6 95-96°C 11.5.89	$>3.0 \times 10^5$	ND/g	ND/g	ND
B2 T=91°C 16.5.89	1.8×10^3	ND/g	ND/g	ND
A3 T=96°C 16.5.89	3.7×10^4	ND/g	ND/g	ND

> = greater than
ND = not detected under the conditions of test used on this occasion

ANALYSED BY: Annette Fordham

Annette Fordham MASM.

Bf

11.8 Appendix F - Class A Pathogen Reduction

(Extract taken from USEPA, Standards for the Disposal of Sewage Sludge.[13])

ontrol temperature, so temperatures ordinarily range from 10 to 30 degrees Celsius, depending on the daily weather conditions. If energy is conserved (e.g., by minimizing air flow and covering the digester), temperatures can increase to the thermophilic range (50 to 60 degrees Celsius). Nominal residence times range from 10 to 40 days. Volatile solids reductions, which indicate a reduction in the ability of the sludge to create odors and attract vectors, is increased by operating at higher temperatures and for longer residence times.

The three types of aerobic digestion processes are conventional semi-batch digestion, conventional (mesophilic) continuous digestion, and autoheated (thermophilic) continuous digestion. In the semi-batch operation, solids are pumped directly from the clarifier into the continually aerated digester. When the digester is full, aeration continues for an additional 2 to 3 weeks. The conventional continuous operation closely resembles the activated sludge process with a flow-through aerobic digester followed by a clarifier-thickener. Many conventional aerobic digesters are operated in the ambient temperature ranges. In the autoheated processes, sludge from the clarifiers is usually thickened to provide a digester feed with greater than four percent solids. In these digesters, thermophilic conditions (50 to 60 degrees Celsius) result from the exothermal heat of substrate oxidation.

Anaerobic Digestion

Anaerobic digestion is the degradation of microbiological organic substance in the absence of oxygen. Primary or secondary sludge is digested in an air-tight reactor for varying periods of time depending on the temperature.

The three basic types of anaerobic digestion are low-rate digestion, high-rate digestion, and two-stage digestion. In low-rate digestion, the sludge is unmixed in the reactor and the processes of sludge thickening and liquid solid separation are carried out simultaneously. In high-rate digestion, the sludge in the reactor is mixed and heated to speed up microbial processing of the sludge. High-rate reactors are operated at either mesophilic (30 to 38 degrees Celsius) or thermophilic (50 to 60 degrees Celsius) temperatures. High-rate reactors have shorter detention times than do low-rate reactors (i.e., 30 to 60 days for low-rate digesters versus 10 to 20 days for high-rate digesters). In the two-stage process, a high-rate digester is linked to a second digester, generally unmixed. The second digester primarily serves as a thickener.

Density of Microorganisms

The density of microorganisms per unit mass of volatile suspended solids is the number of microorganisms divided by the mass of volatile suspended solids in the sewage sludge. The number of microorganisms may be colony-forming units or most probable number of bacteria, plaque-forming units of viruses, or the actual number, by count, of either protozoan cysts or helminth ova.

The Agency is defining the density of microorganisms in terms of volatile suspended solids because these organisms are associated with volatile suspended solids (i.e., organic material) in the sewage sludge. The Agency invites comment on this approach.

Specific Oxygen Uptake Rate

Specific oxygen uptake rate (SOUR) is the rate at which bacteria consume oxygen in a liquid sewage sludge that has been treated in an aerobic process (i.e., mass of oxygen consumed per unit time, per unit mass of sewage sludge solids). A high SOUR indicates there is a large and active bacteria mass in the sewage sludge and the sewage sludge is likely to putrefy rapidly. A low SOUR indicates that the bacteria in the sewage sludge have consumed available food sources and the sewage sludge will not putrefy rapidly. The SOUR standard of 1 milligram of oxygen per hour, per gram of sewage sludge solids or less is used as one of the indicators that the treatment has met the vector attraction reduction requirements.

The SOUR standard is only appropriate for sewage sludge or compost that has undergone aerobic digestion and has a high proportion of aerobic bacteria. Therefore, untreated, limed, and anaerobically digested sewage sludge are not eligible to use this standard.

Volatile Suspended Solids

Volatile suspended solids is that portion of the total solids in sewage sludge that is removed when the sewage sludge is burned at 550 degrees Celsius in the presence of excess air. Microbiological densities are measured in terms of volatile suspended solids in the sewage sludge because these microbes are associated with the volatile suspended fecal material.

Pathogen Reduction Requirements (§ 503.52)

Section 503.52 proposes three classes of pathogen reduction to achieve the objective of reducing pathogenic organisms below levels of detection. EPA developed the three classes or levels of pathogen reduction (i.e., Class A, Class B, and Class C) to provide treatment works greater flexibility in reducing the risk of infection and disease from pathogens than was allowed in 40 CFR 257.3-6. Treatment works may meet the pathogen reduction requirement by treating the sewage sludge to the Class A performance standard. The requirement may also be met by treating the sewage sludge to a Class B or a Class C performance standard and by placing time restrictions on public access to the land where the sewage sludge is applied and placing time restrictions on growing and harvesting crops and grazing animals on that land. These access and use restrictions are not applicable to sewage sludge disposed of in monofills or on surface disposal sites because crops are not grown on monofills or surface disposal sites and because the access restrictions for these disposal practices are more stringent than the access restrictions for land application of sewage sludge.

Class A

Class A pathogen reduction is achieved by processing the sewage sludge. Generally, this will involve composting the sewage sludge or using other processes that increase the temperature of the sewage sludge to 50 to 60 degrees Celsius.

To achieve Class A reduction, the pathogenic bacteria, viruses, protozoa, and helminth ova in the sewage sludge must be reduced to below detectable limits. By requiring that bacteria, viruses (*Salmonella* sp.), protozoa, and helminth ova are all below levels of detection, the Agency believes that these organisms will not infect individuals or animals.

The proposed methods to be used in measuring each of these organisms are presented in § 503.81(b) and discussed later in the preamble. As part of that discussion the Agency is inviting comments on the methods.

An alternative requirement is presented in today's proposed rule for Class A pathogen reduction because of the difficulty in demonstrating that all four types of pathogens are below detectable limits. EPA is proposing that when the temperature of sewage sludge is raised (53 degrees Celsius for 5 days or 55 degrees Celsius for 3 days or 70 degrees Celsius for one-half hour) and the density of fecal coliforms and fecal streptococci (enterococci) per gram of volatile suspended solids are each equal to or less than 100, the Class A pathogenic reduction requirements are achieved.

...cal coliforms and fecal streptococci ...benign organisms present in fecal material. They are used as indicators of the presence of fecal material. If their densities are high, the risk of infectious levels of pathogenic organisms is also high. Agency data indicate that when coliform densities in processed sludge are low (100 per gram of volatile suspended solids or less), *Salmonella* are absent and when coliform densities are high, *Salmonella* are present (Reference number 78). Thermal processes are about as efficient in destroying pathogenic organisms as they are in destroying fecal indicators, but the fecal indicators are present in much higher densities. When the fecal indicators are reduced to very low values, the likelihood of pathogen survival is negligible. Research also shows that thermal processes must raise the temperature of the sludge to 53 degrees Celsius or above to ensure the destruction of helminth ova (*Ascaris* sp.) (Reference number 78). Other processes may reduce fecal indicator densities to low levels but may not reduce all of the pathogens in sewage sludge to acceptable levels. For example, ionizing radiation is more effective against bacteria than against viruses. For this reason, viruses may be present in the sewage sludge even though the fecal indicators are below the 100 gram level. Another example is chemical treatment of sewage sludge. Chemical treatment may reduce pathogenic bacteria and viruses, but may not reduce helminth ova because the ova are protected by a ...ll that may be impervious to chemicals. Therefore, measurement of fecal indicators may be used only when thermal processes raise the temperature of the sludge for the specified periods of time.

The Agency invites comments on applying the fecal indicator alternative only to processes that raise the temperature of the sewage sludge to at least 53 degrees Celsius and solicits data on the correlation of pathogens to fecal indicator organisms for other technologies. The Agency also requests comments on both the use of indicator organisms to measure pathogen reduction and on the use of the density of 100 per gram of volatile suspended solids value for fecal coliforms and fecal streptococci/enterococci. The Class A pathogen reduction must be completed prior to or must be concurrent with the processes that are used to meet the vector attraction reduction requirements (see § 503.52(a)(3)). The objective of this requirement is never to leave a sewage sludge that is required to meet Class A requirements nearly devoid of vegetative bacteria unless there is something present that inhibits bacterial growth. The inhibiting factor may be dryness, presence of certain chemicals, or presence of vegetative bacteria. If the Class A process that reduces pathogens follows the process for reducing vector attraction (for example, pasteurization after anaerobic digestion), vegetative bacteria are destroyed. Subsequent contamination by pathogenic bacteria could result in explosive regrowth. If the situation were reversed, the presence of nonpathogenic bacteria that caused the digestion and reduced the value of the sludge as an energy source would severely limit potential for explosive regrowth. This does not apply to Class B and Class C pathogen reduction because competitive bacterial organisms that hinder regrowth are present in the sewage sludge.

Since the Class A pathogen requirements reduce pathogenic organisms to levels unlikely to cause an infectious dose, the Agency is not imposing restrictions on access to or use of the land for any period of time. Access is restricted for non-agricultural lands until a vegetative cover is established, but only to keep individuals from sitting in or tracking sewage sludge off the field. Sewage sludge that is distributed and marketed must meet Class A pathogen reduction requirements. It is optional for other methods of use or disposal.

Class B

To reduce pathogenic organisms to safe levels, Class B pathogen reduction requirements use a combination of treatment and time restrictions on access to and use of land to which the sewage sludge is applied. The level of pathogenic organism reduction or the density of indicator organisms is based on well-operated treatment works that use primary settling, followed by activated sludge treatment and anaerobic digestion. For treatment works to achieve the Class B pathogen reductions, they must either demonstrate that the treatment processes reduce the average density of pathogenic bacteria and of viruses per unit mass of volatile suspended solids in the sludge two orders of magnitude lower than those densities in the incoming wastewater or demonstrate that the densities of each of the fecal indicator organisms is 6 $\log_{10}$ or less.

For example, if the influent to the treatment work shows that the average density of pathogenic bacteria per unit mass of volatile suspended solids is 1 million (10^6) and that the average density of viruses per unit mass of volatile suspended solids is 10,000 (10^4), after treatment, the processed sludge must show pathogenic bacteria densities of 10,000 (10^4) and virus densities of 100 (10^2) per unit mass of volatile suspended solids.

No requirements for reduction in protozoan cysts or helminth eggs are specified. Protozoan cysts are believed to be greatly reduced in numbers by sludge processing and even if they were not greatly reduced, their numbers are reduced through environmental exposure on land. Helminth eggs are not significantly reduced by processing and their densities decline slowly in the environment. The long period when growing food crops with the harvested portion below the ground is not allowed (5 years or 18 months if no viable helminth ova are found) and the 12-month period during which public access to the fields is restricted protect the public against possible ingestion of viable infective helminth eggs.

The test data that the Agency has on the reductions in pathogenic organisms are based on relative $\log_{10}$ reductions. The Agency found that absolute numbers varied significantly between facilities depending on the influent to the treatment work, the method used to measure the pathogenic organisms, and the investigator conducting the measurements. However, for fecal coliforms and fecal streptococci, the Agency does have data indicating that when treatment of the influent includes a well-operated physical or biological process and these processes are combined with alkali additions, chlorine additions, or storage of the sewage sludge, the log density of fecal coliforms and fecal streptococci each are 6.0 or less. Reductions in fecal indicators correlate well with reductions in pathogenic bacteria and viruses when a combination of processes is used to treat the influent and the sewage sludge. Current data also indicate that the logarithms of the densities of fecal coliforms and fecal streptococci in the influent to the treatment works do not vary significantly for different wastewater. For these reasons, the Agency believes an absolute value for fecal indicators can be used to indicate that the Class B pathogen reduction has been achieved. The Agency invites comments on this alternative requirement and on limiting the applicability of the requirement to the use of certain technologies. The Agency also solicits data on the correlation of fecal coliforms and fecal streptococci to pathogenic bacteria and viruses. The access and use restrictions discussed later in this section of the preamble also

11.9 Appendix G - Analysis Reports for 60kW Plant

BACAS

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23 July 1990

Mr Paul Mourtos
MARC
University of Wollongong

REPORT 1: SAMPLE DATE 25-6-90

Lab No.	Fecal Coliforms (org/gram)	E.coli (org/gram)	Salmonella
3401	0	0	Negative
3402	0	0	Positive
3403	0	0	Positive
3404	1×10^3	1×10^3	Positive
3405	No fecal coliforms detected (confluent)	1×10^4	Positive
3406	2×10^4	-	Positive
3407	No fecal coliforms detected (confluent)	-	Positive
3408	No fecal coliforms detected (confluent)	-	Positive

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23 July 1990

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REPORT 2: SAMPLE DATE 26-6-90

Lab No.	Fecal Coliforms (org/gram)	E.coli (org/gram)	Salmonella
3465	0	0	Negative
3466	0	0	Positive
3467	0	0	Positive
3468	0	0	Positive
3469	2×10^3	2×10^2	Positive
3470	2×10^3	2×10^2	Positive
3471	2×10^2	2×10^2	Positive
3472	2×10^2	2×10^2	Positive
3473	No fecal coliforms detected (confluent)	-	Positive
3474	No fecal coliforms detected (confluent)	-	Positive

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29 November 1990
(Ref: 5104-5114)

Mr Paul Mourtos
Microwave Applications Research Centre
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UNIVERSITY OF WOLLONGONG

ANALYSIS OF SLUDGE SAMPLES SUBMITTED 24.10.90

Sample	Lab no.	Fecal Strep.	Total Coliform (org/g)	Fecal Coliform (org/g)	Salmonella
1	5104	Negative	4×10^4	4×10^4	Negative
2	5105	Negative	1×10^5	7×10^4	Negative
3	5106	Positive	1×10^3	4×10^5	Positive
4	5107	Negative	6×10^4	1×10^4	Negative
5	5108	Negative	7×10^5	2×10^4	Negative
6	5109	Negative	3×10^6	6×10^3	Positive
7	5110	Positive	TNTC	TNTC	Positive
A	5111	Positive	3×10^4	3×10^5	Positive
B	5112	Positive	4×10^4	2×10^5	Positive
C	5113	Negative	TNTC	TNTC	Positive
D	5114	Negative	TNTC	TNTC	Positive

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28 November 1990
(Ref: 5301-5309)

Mr Paul Mortous
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ANALYSIS OF SLUDGE SAMPLES SUBMITTED 7.11.90

Sample	Lab no.	Fecal Strep.	Fecal Coliform (org/g)	E.coli (org/g)	Salmonella
1	5301	Negative	Not detected	Not detected	Negative
2	5302	Negative	Not detected	Not detected	Negative
3	5303	Negative	Not detected	Not detected	Negative
4	5304	Negative	6×10^2	Not detected	Negative
5	5305	Negative	Not detected	Not detected	Negative
A	5306	Positive	6×10^3	6×10^3	Positive
B	5307	Positive	8×10^3	8 x 103	Positive
C	5308	Negative	20	20	Positive
D	5309	Negative	100	100	Positive

Trevor W. Lewis
Director